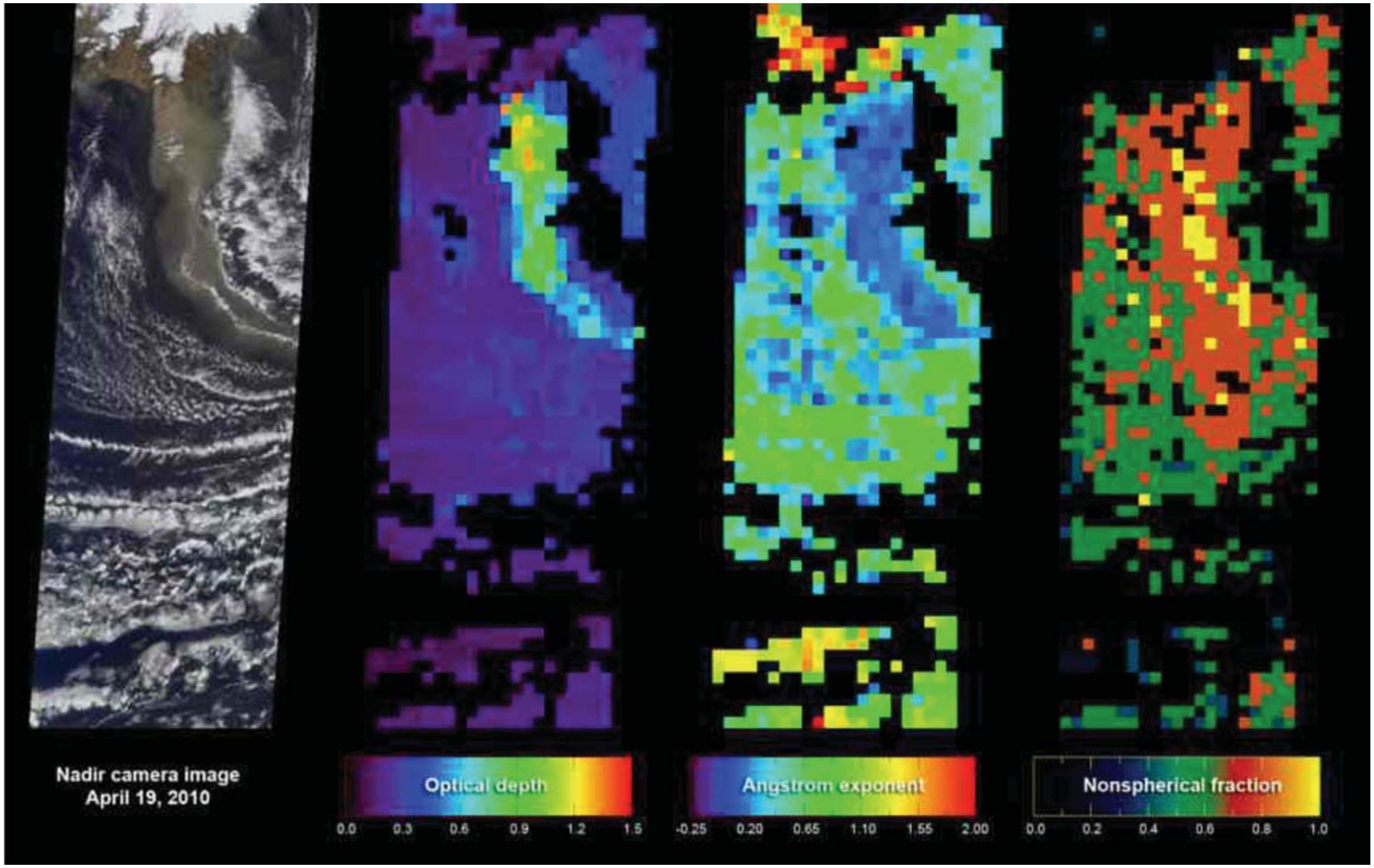
Aerosol Remote Sensing From Space – Where We Stand, Where We′ re Heading

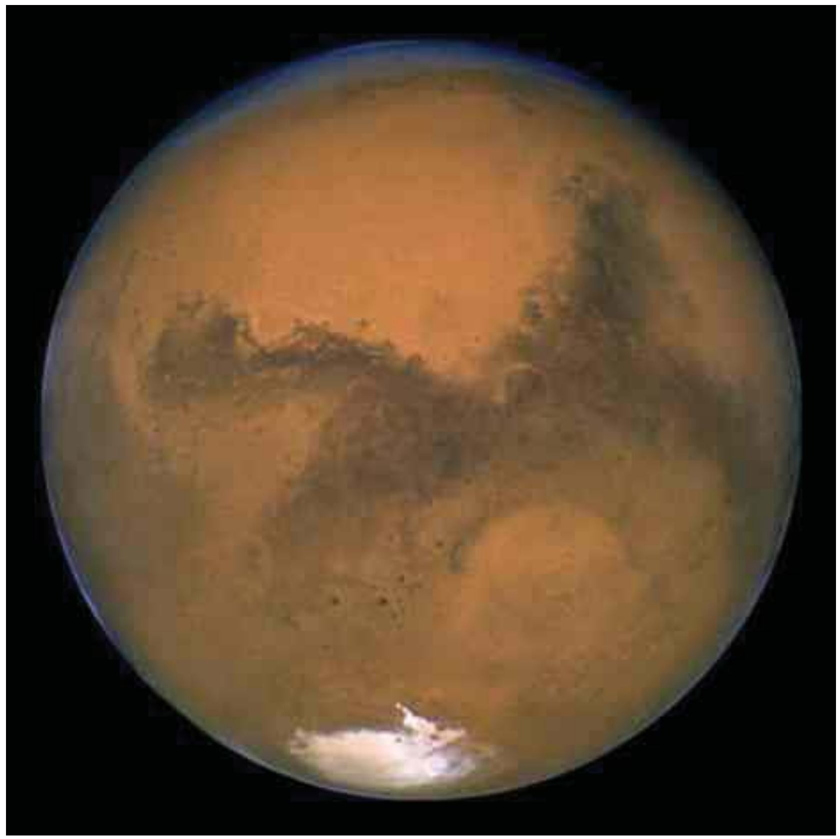
Ralph Kahn *NASA Goddard Space Flight Center*



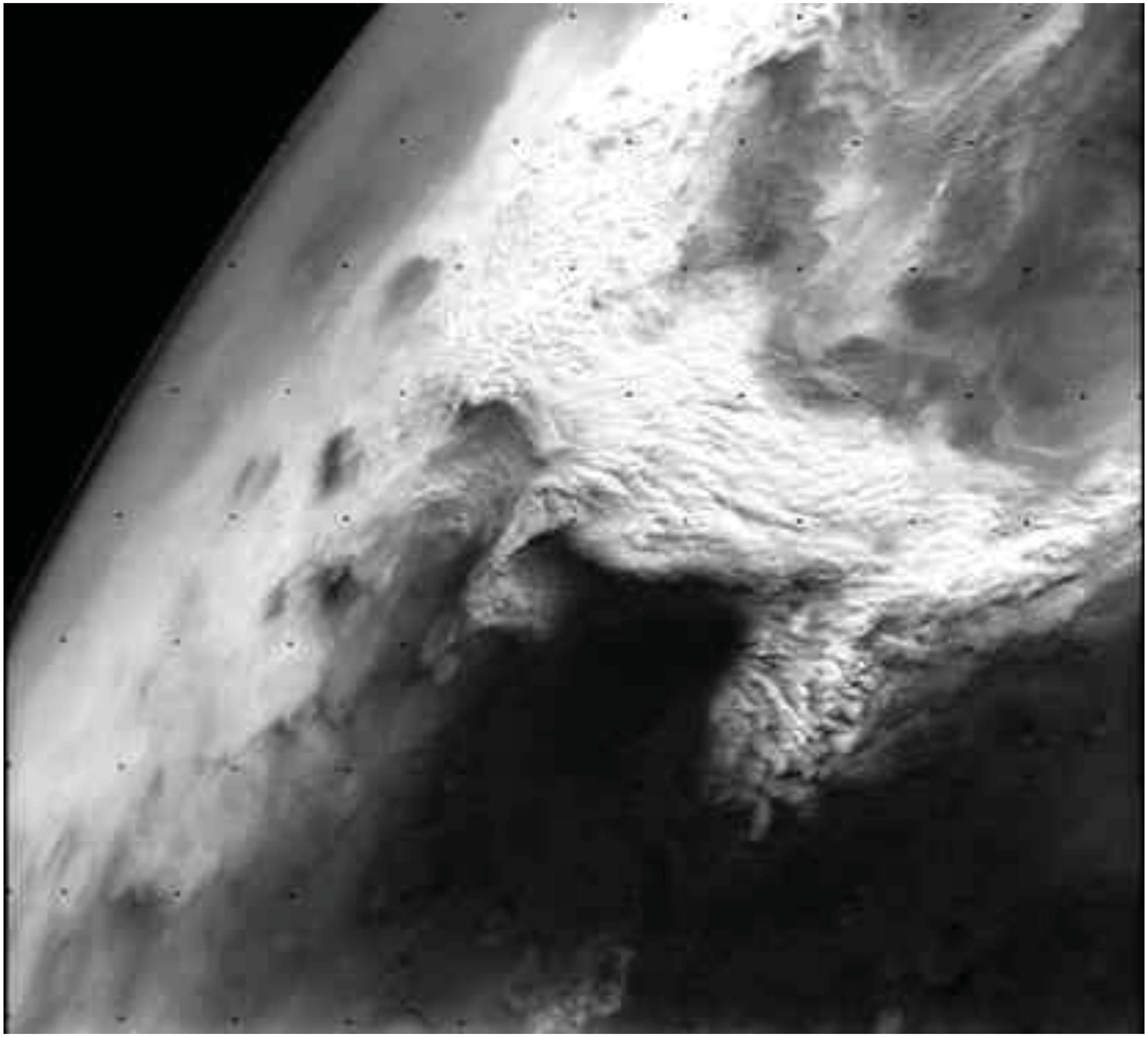
Eyjafjallajökull Volcano Ash Plume – MISR Aerosol Retrieval – April 19, 2010

MISR Team, JPL and GSFC

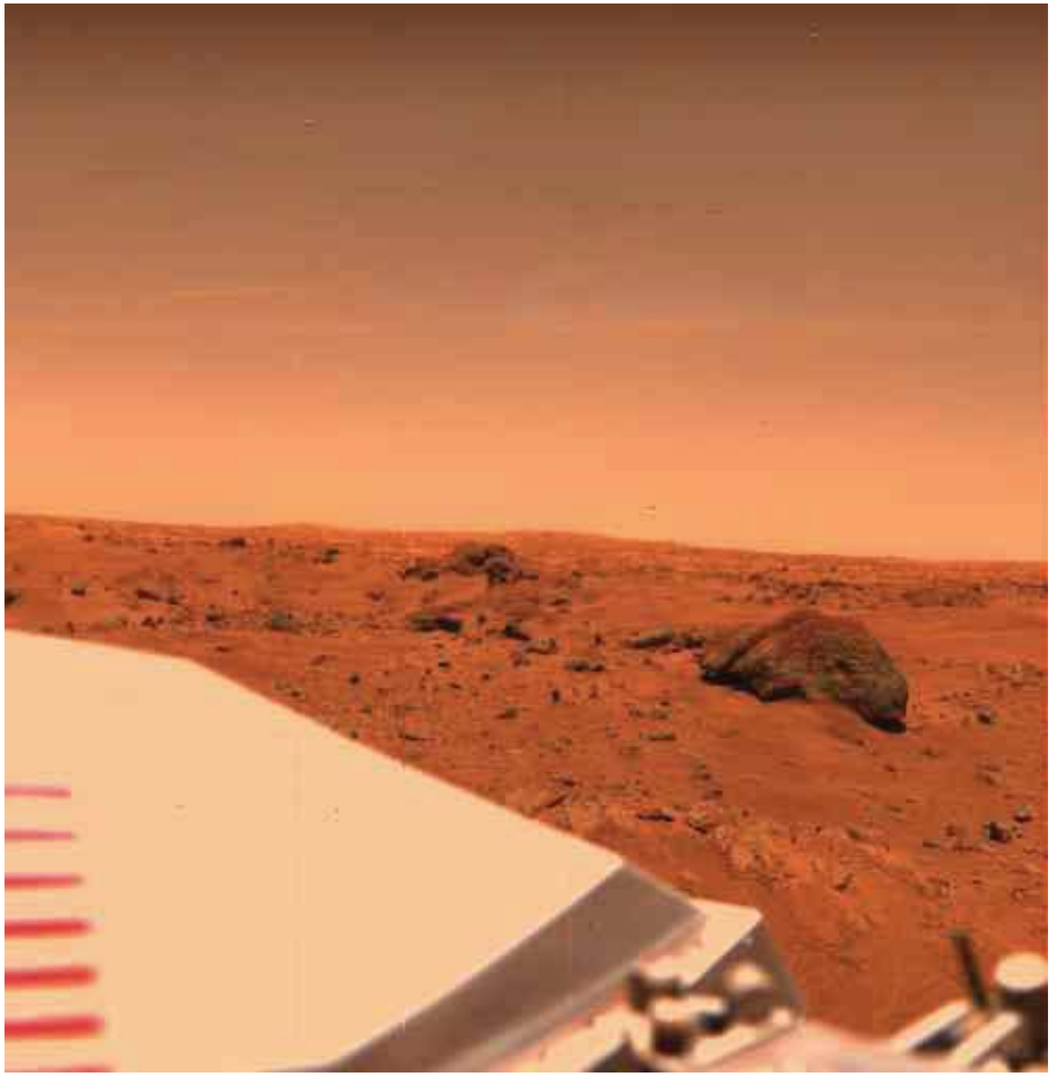
Beginning at the Beginning



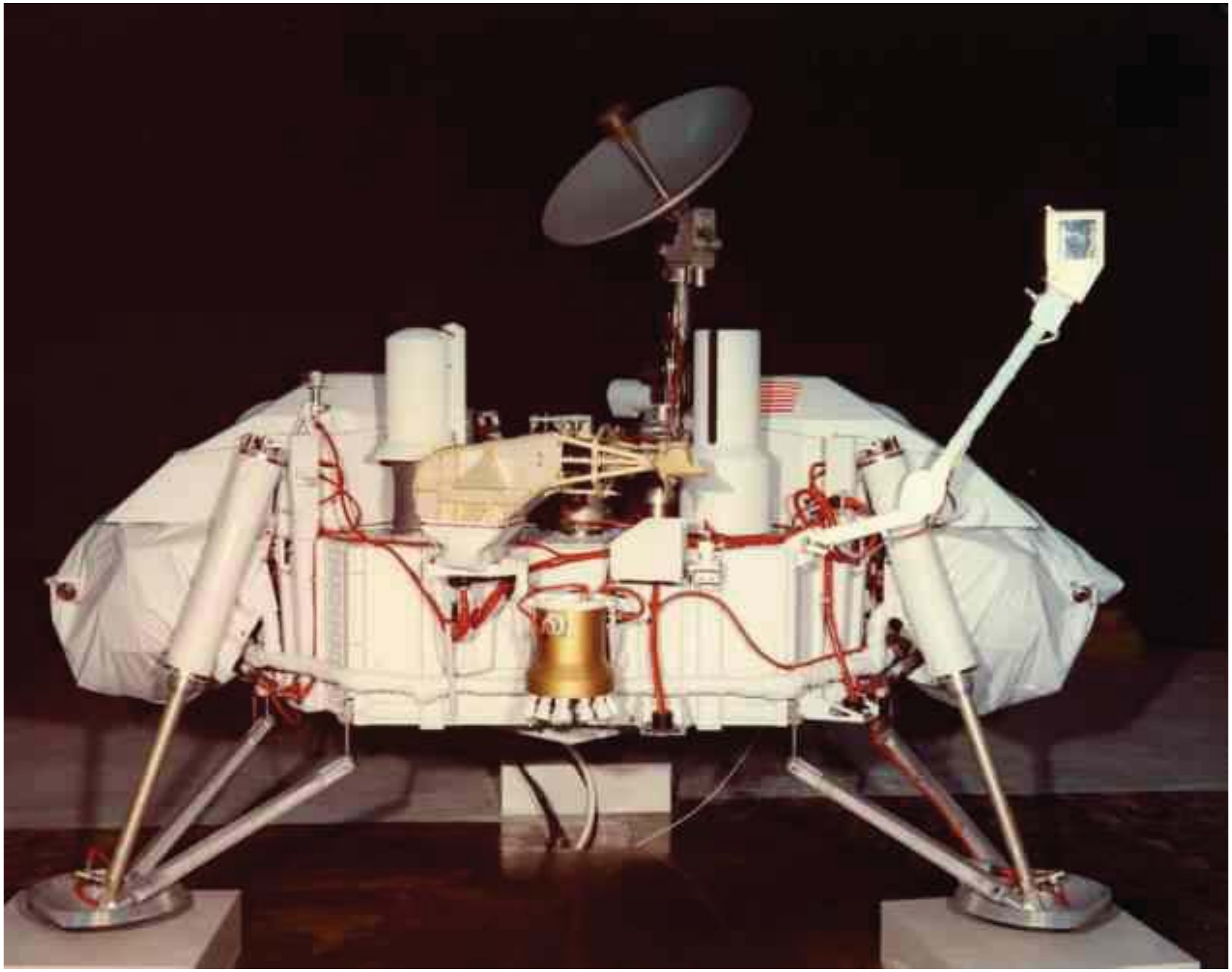
Mars Dust Storm – Viking Orbiter 1976!



Martian Sky – Viking Lander 1, 1976!



The Viking Lander!



Sunset on Mars – Viking Lander 1, 1976!

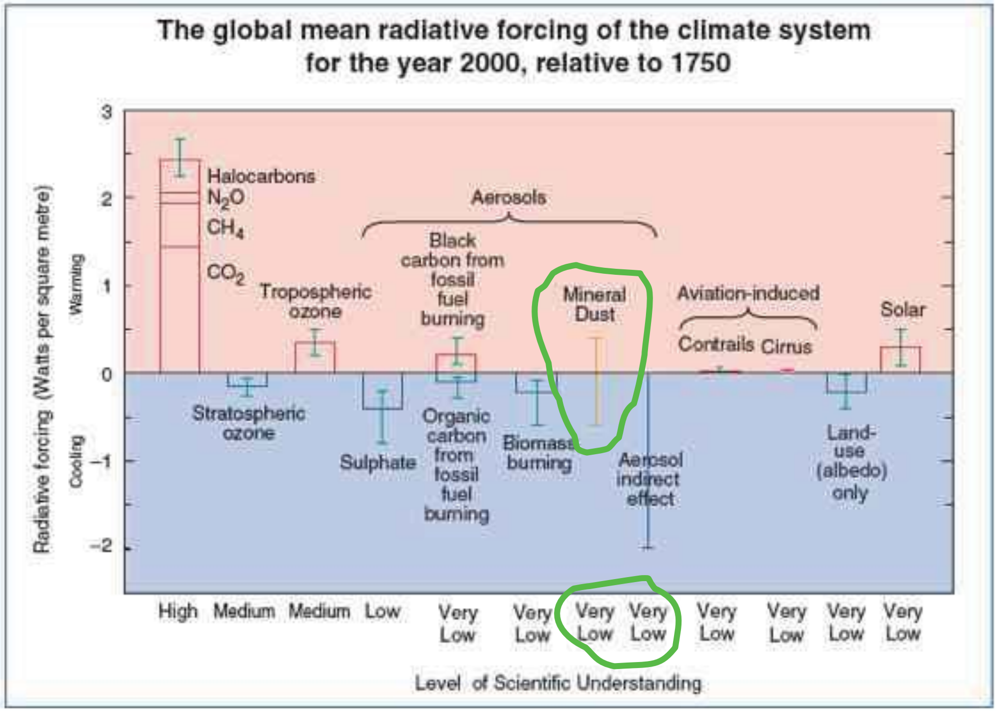
SeaWiFS – Sahara Dust over Canary Islands 06 March 1998

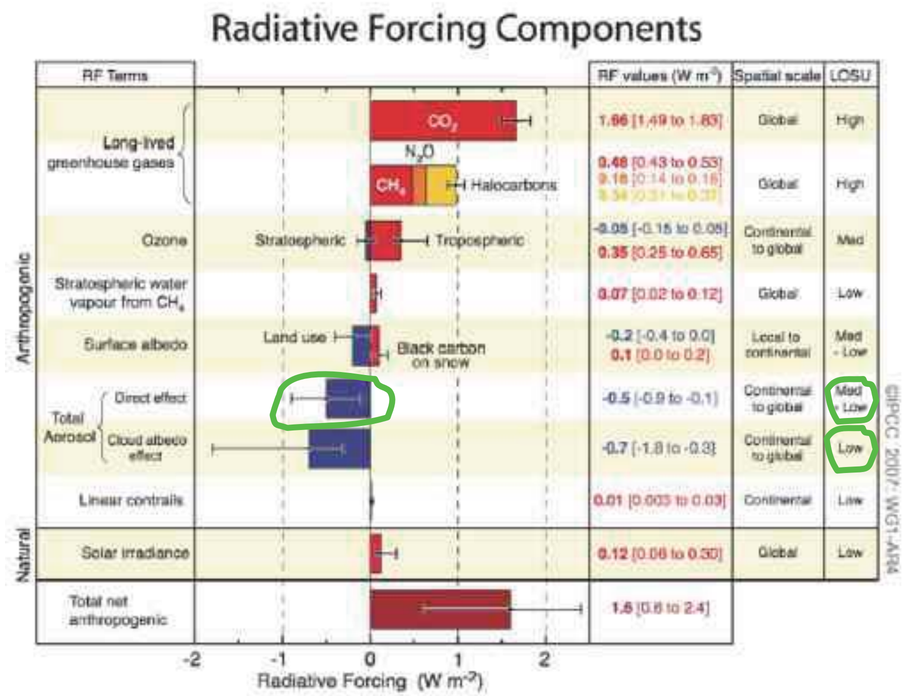
Station Fire near JPL, Pasadena CA August-September 2010

MODIS – ***Fires in Alaska*** *01 July 2004 21:40 UTC*

Mt. Etna Plume Structure 27-30 October 2002

Even DARF and Anthropogenic DARF are *NOT* Solved Problems (Yet)!





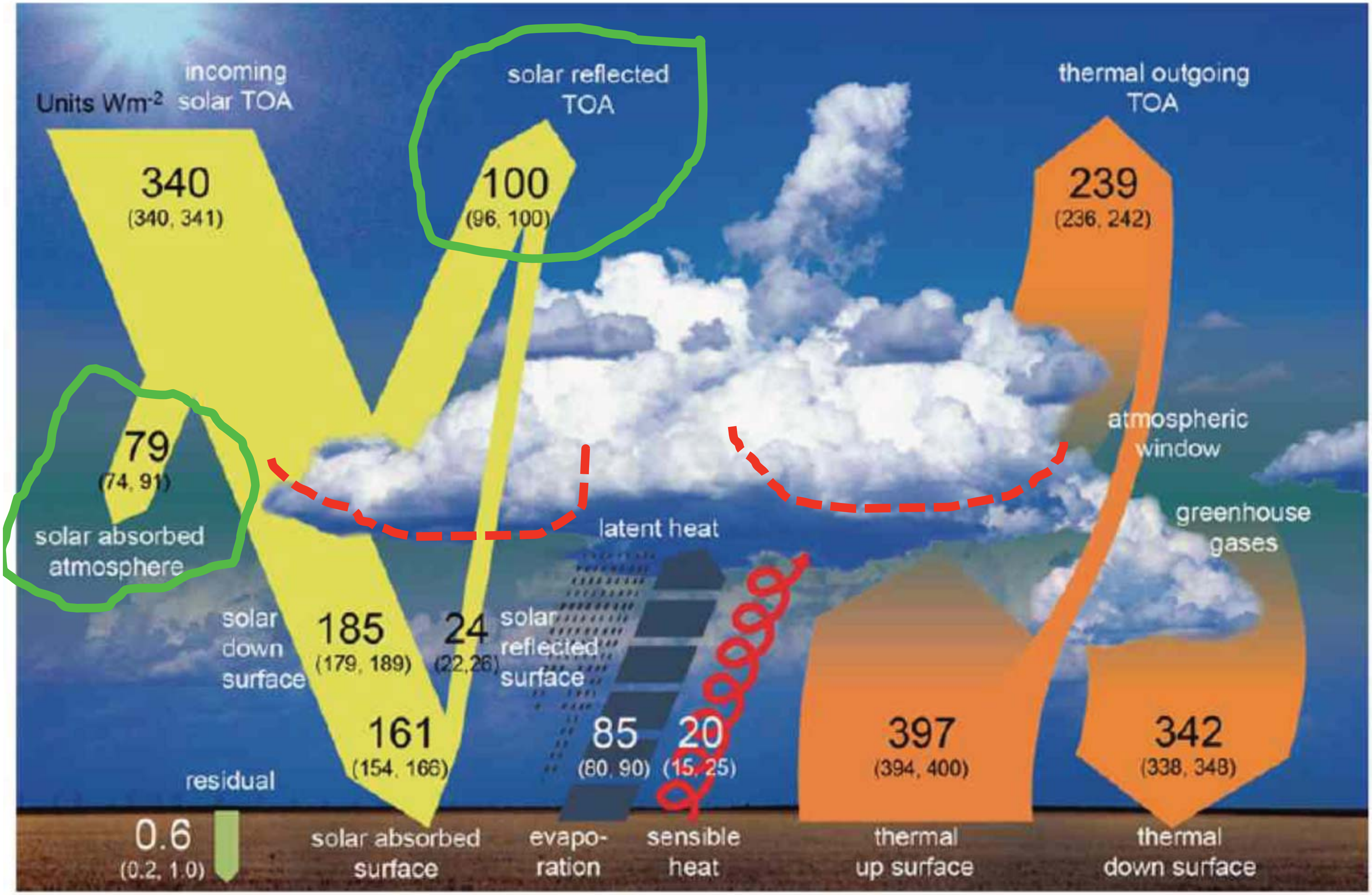
RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
CO_2	1.66 [1.49 to 1.83]	Global	High
N_2O / CH_4 / Halocarbons	0.48 [0.43 to 0.53] 0.16 [0.14 to 0.18] 0.34 [0.31 to 0.37]	Global	High
Ozone	-0.05 [-0.15 to 0.05] 0.35 [0.25 to 0.65]	Continental to global	Med
Stratospheric water vapour from CH_4	0.07 [0.02 to 0.12]	Global	Low
Surface albedo	-0.2 [-0.4 to 0.0] 0.1 [0.0 to 0.2]	Local to continental	Med - Low
Total Aerosol: Direct effect	-0.5 [-0.9 to -0.1]	Continental to global	Med - Low
Total Aerosol: Cloud albedo effect	-0.7 [-1.8 to -0.3]	Continental to global	Low
Linear contrails	0.01 [0.003 to 0.03]	Continental	Low
Solar irradiance	0.12 [0.06 to 0.30]	Global	Low
Total net anthropogenic	1.6 [0.6 to 2.4]		

FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}

IPCC AR3, 2001
(Pre-EOS)

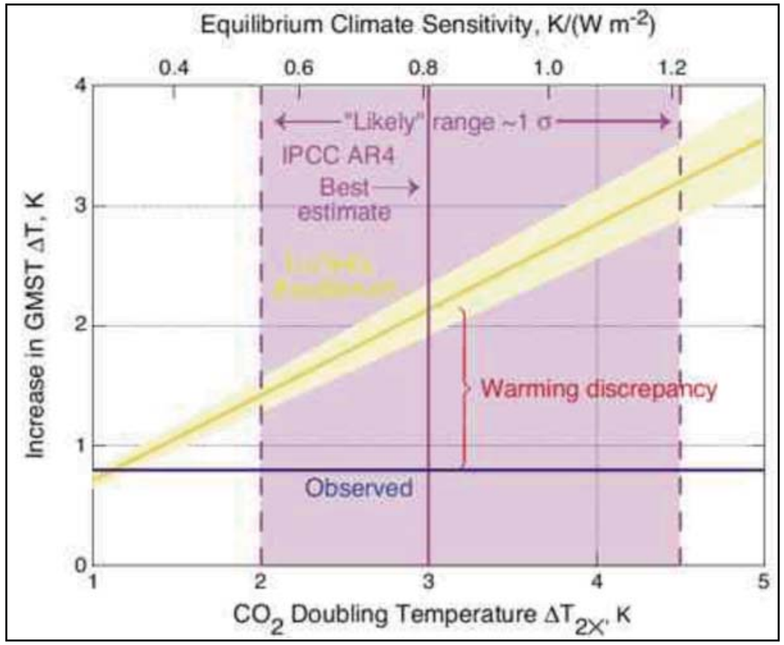
IPCC AR4, 2007
(EOS + ~ 6 years)

Global Energy Flows (W/m²)



Wild et al., BAMS 2012!

Climate Sensitivity, Aerosols, and Climate Prediction



Schwartz et al., 2010

F! ∀! S! = ! T!

Effective! Forcing !   Climate! Sensitivity!   Response!

- ***Models are constrained by*** historical global mean surface temperature (***GMST***) ***change***!
- Forcing by LL greeenhouse gas increase since pre-industrial: ~ 2.6 W/m^{2}!
- ! GMST ***Expected***: ~ 2.1 K;   ! GMST ***Observed***: ~ 0.8 K !
- ***Discrepancy dominated by Aerosol Forcing vs. S*** (disequilibrium, natural variation, etc. are less)!
- ***Model Aerosol Forcing choices compensate for Climate Sensitivity differences*** (*Kiehl, GRL 2007*)!

!

→ Aerosol forcing uncertainty directly impacts confidence in model predictions
From a policy perspective, this bears upon the *urgency of mitigation* efforts

Aerosol Contribution to Global Climate Forcing!

- Cloud-free, global, ***Over-ocean***, vis, TOA DARF relative to zero aerosol: **-5.5 ± 0.2** W/m^2 !

  This is a ***measurement-based*** value, with ***uncertainty based on diversity*** among estimates!
  (actual uncertainties are probably larger)!

!

- Taking 20% of aerosol to be anthropogenic, the ***human-induced component*** is: **-1.1 ± 0.4** W/m^2!

!

!

- Global TOA ***anthropogenic total*** ARF relative to pre-industrial: **-1.3 (-2.2 to -0.5)** W/m^2 !

  This is a ***model-based*** value, with ***uncertainty defined as diversity*** among estimates;!
  (actual uncertainties are probably much larger)!

!

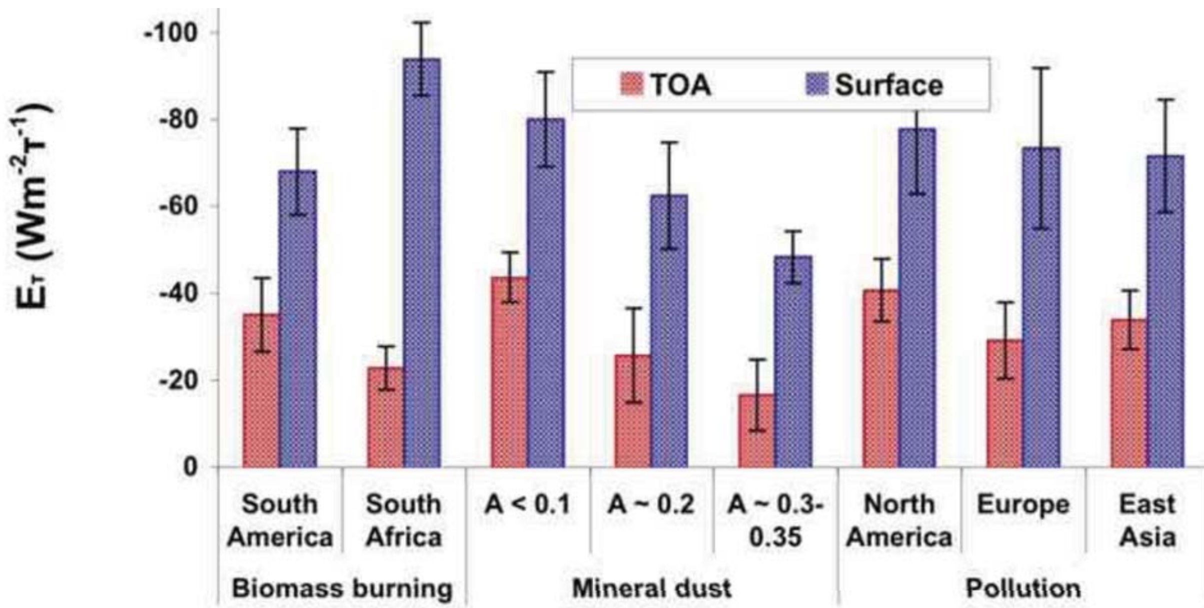
- The models tend to agree on global AOD (as constrained by satellite & surface obs.), !
  but differ on ***regional-scale AOD***, aerosol ***SSA***, and ***vertical distribution***

From: *CCSP - SAP 2.3*, 2009!

How Good is "*Good Enough*"??

AOD Alone is Not Enough –
Even for Direct Aerosol Radiative Forcing

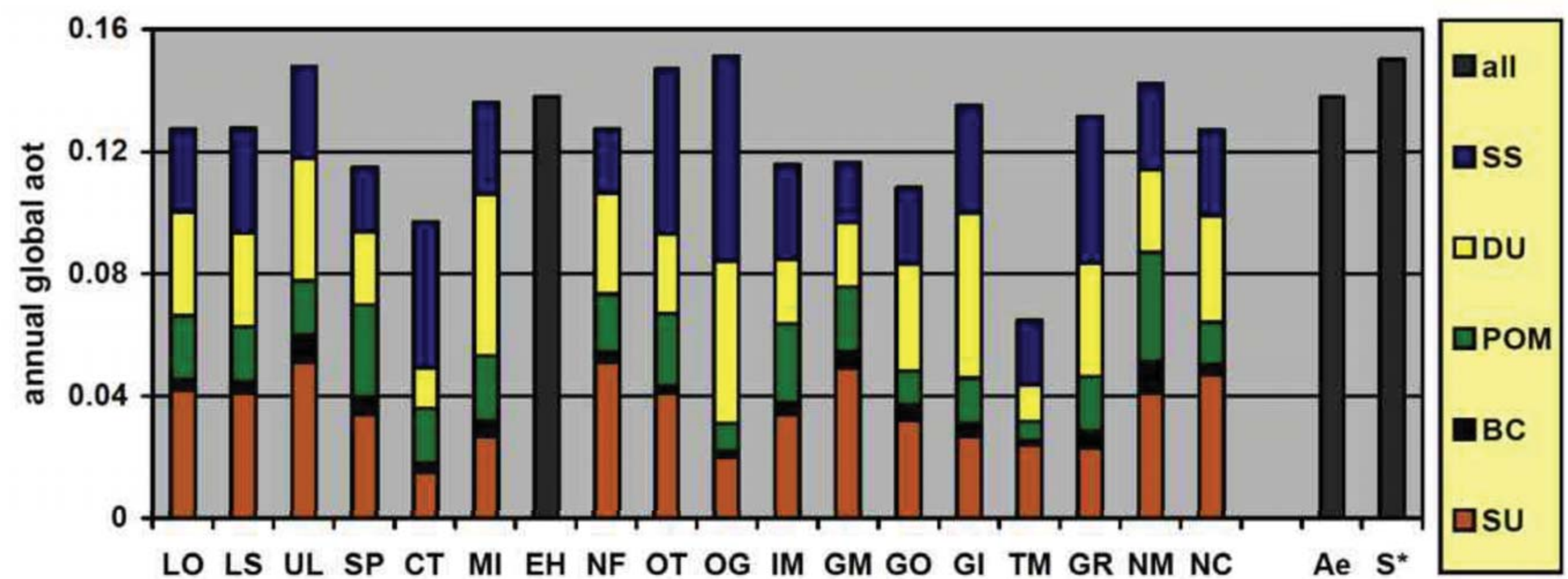
Direct Aerosol Radiative *Forcing Efficiency* per unit AOD!



From: Zhao et al., JGR 2005

- ***Aerosol SSA, Vert. Dist.,*** and ***Surface Albedo*** critical, esp. for ***Surface Forcing***!
- For ***Semi-direct Forcing***, ***Aerosol SSA*** and ***Vertical Distribution*** are critical!

Constraining DARF – The Next Big Challenge



Ae= AERONET; S*= Satellite composite!

Kinne et al., ACP 2006

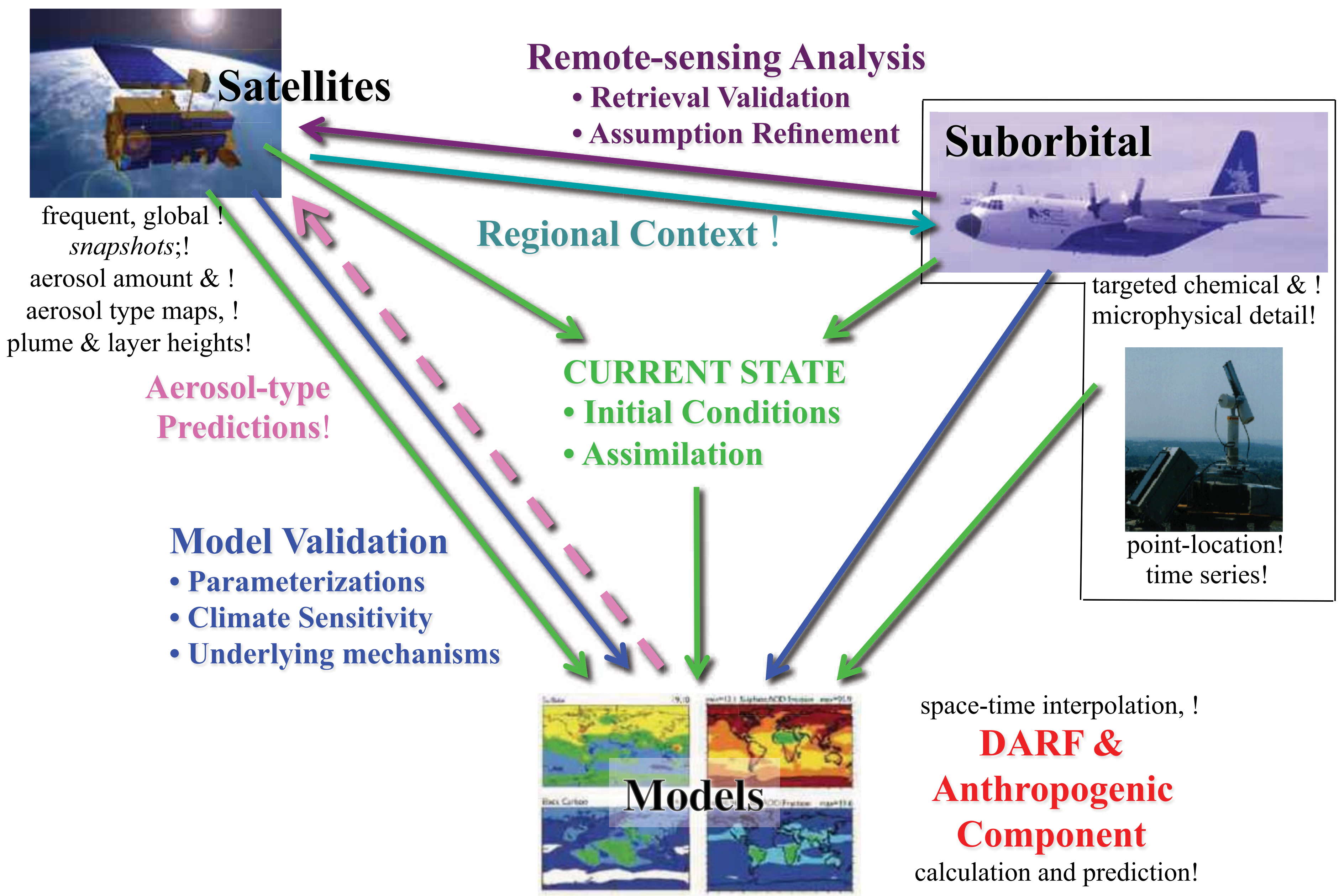
• Agreement among models is ***increasingly good for AOD***, !
given the combined ***AERONET***, ***MISR***, and ***MODIS*** constraints!

• The next big observational challenge: !
Producing ***monthly, global maps of Aerosol Type*** !

How Good is *Good Enough*?

Instantaneous AOD & ***SSA*** uncertainty upper bounds for ~1 W/m^2 TOA DARF accuracy: **~ 0.02**

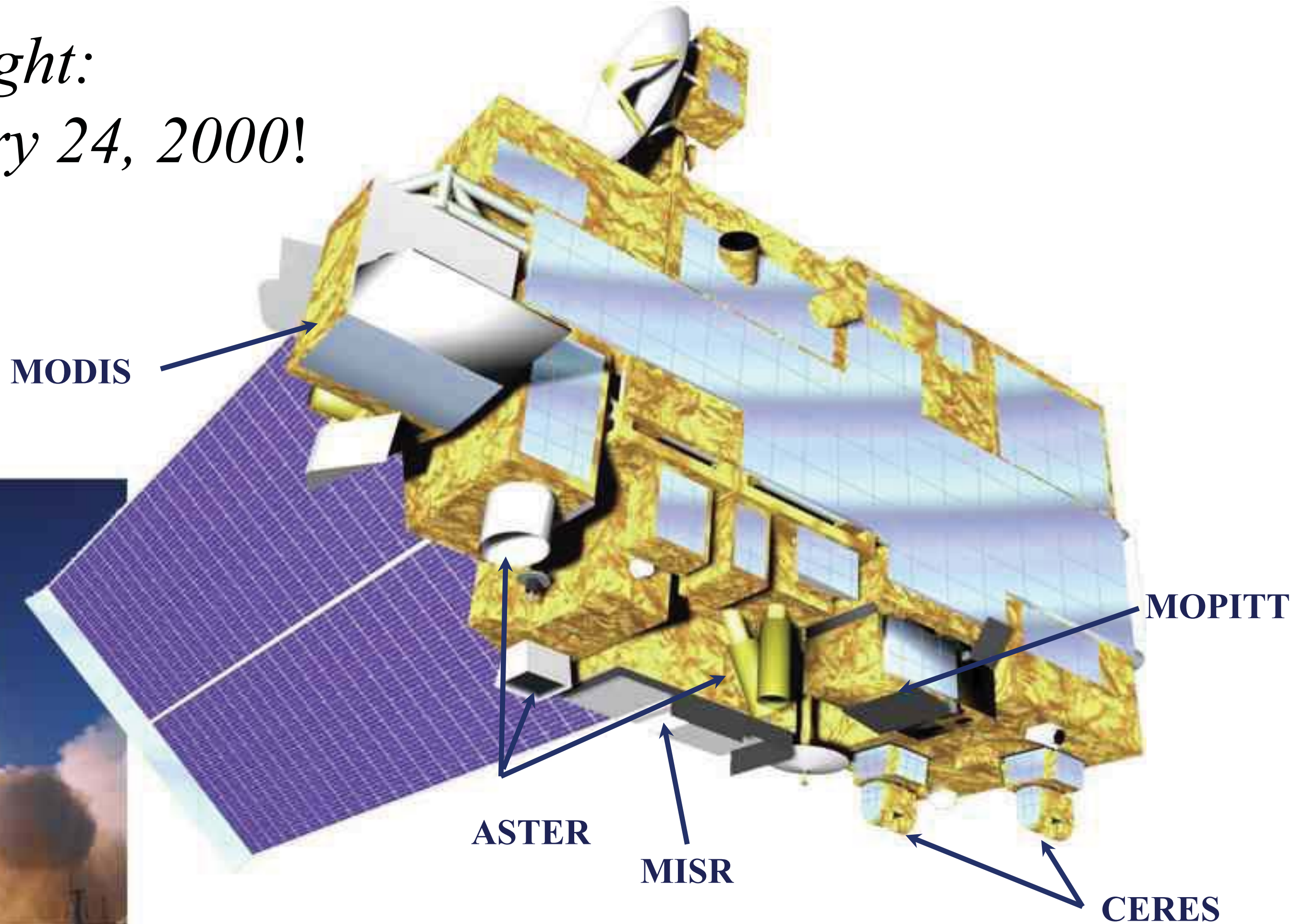
CCSP - SAP 2.3, 2009!



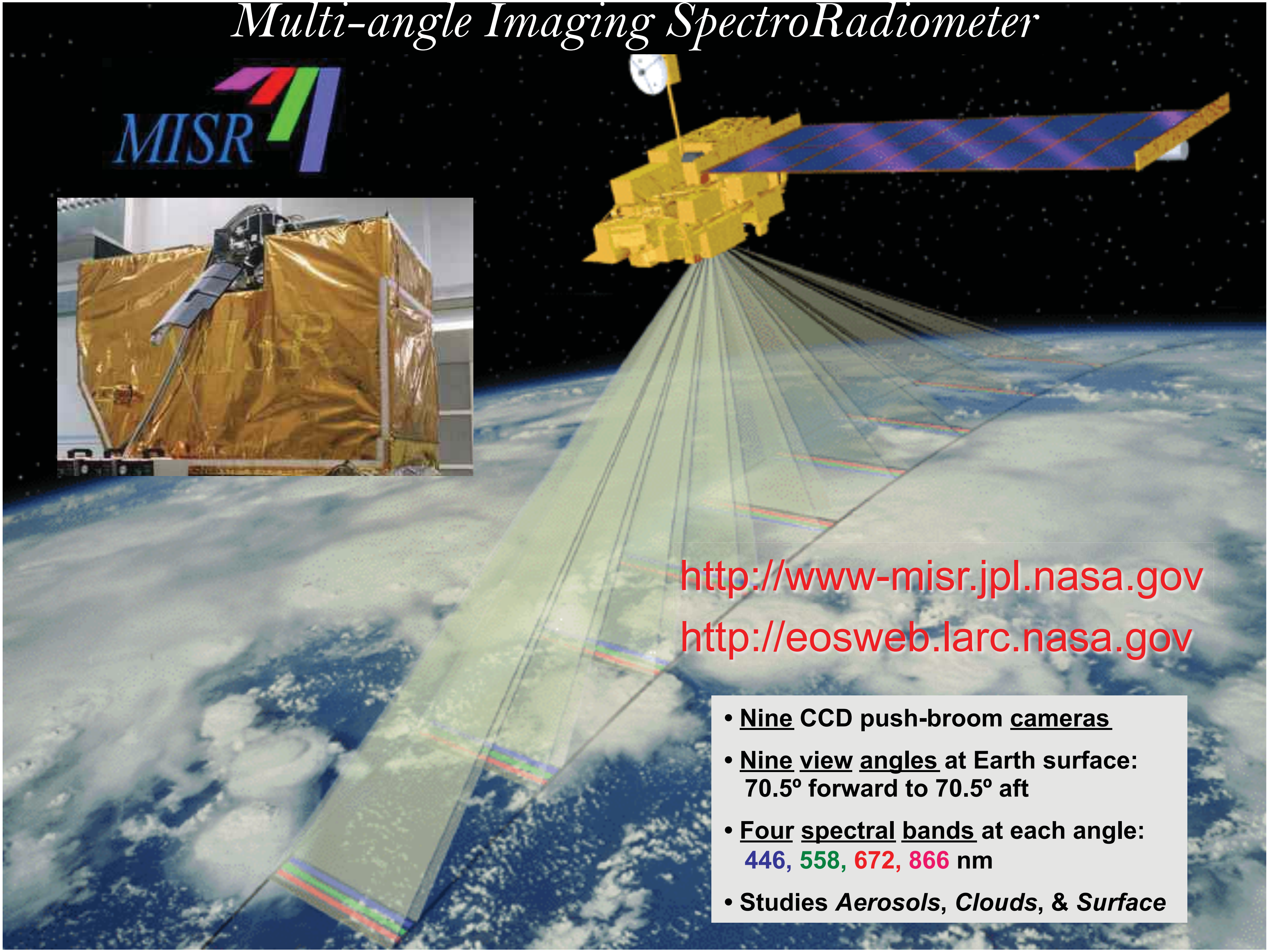
Kahn, Survy. Geophys. 2012

The NASA Earth Observing System's Terra Satellite

First Light:
February 24, 2000



Source: Terra Project Office / NASA Goddard Space Flight Center

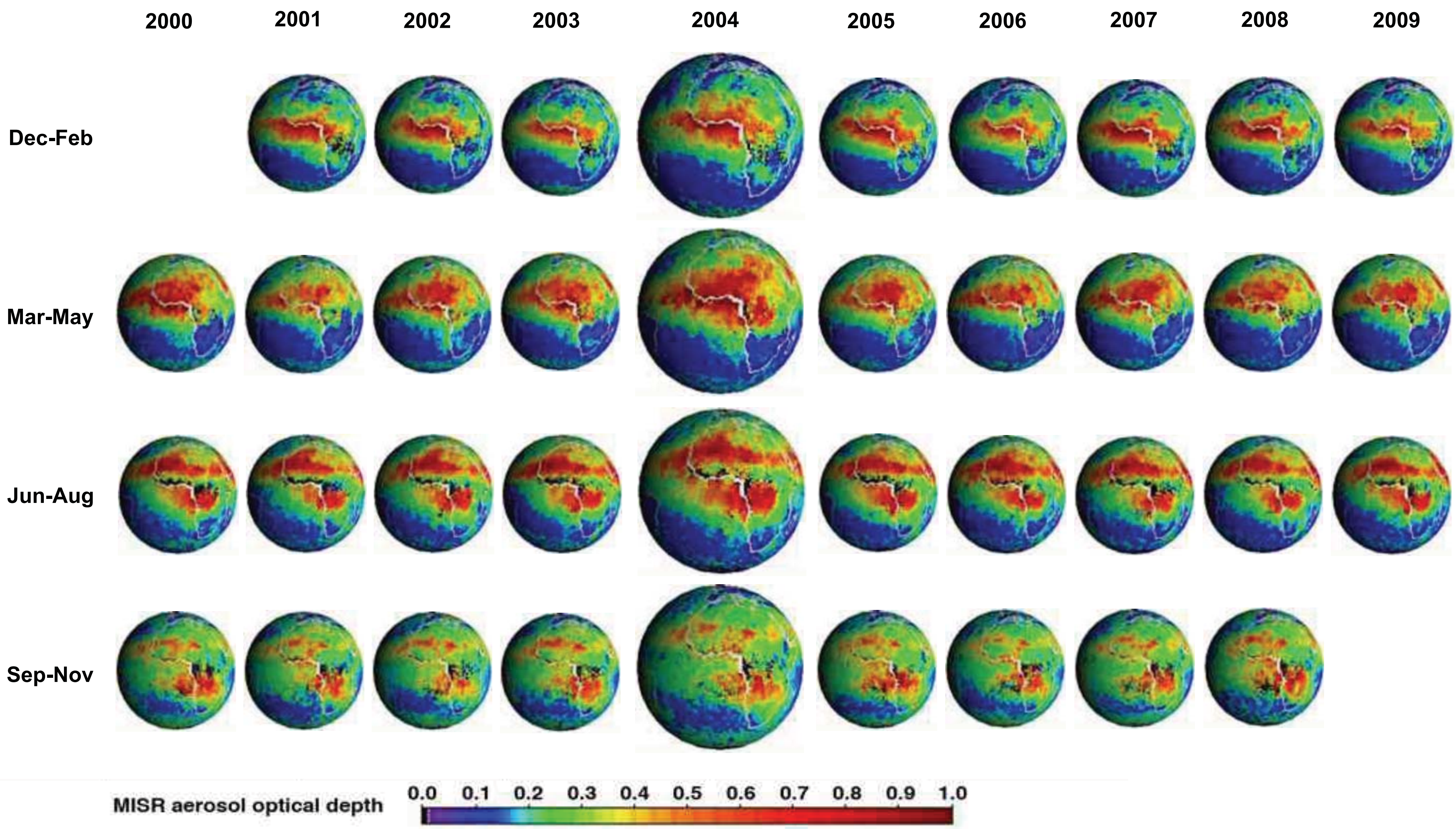


Multi-angle Imaging SpectroRadiometer
MISR
http://www-misr.jpl.nasa.gov
http://eosweb.larc.nasa.gov
• Nine CCD push-broom cameras
• Nine view angles at Earth surface: 70.5º forward to 70.5º aft
• Four spectral bands at each angle: 446, 558, 672, 866 nm
• Studies Aerosols, Clouds, & Surface

Aerosol Retrievals –

Aerosol Optical Depth!

Ten Years of Seasonally Averaged !
Mid-visible Aerosol Optical Depth from **MISR**

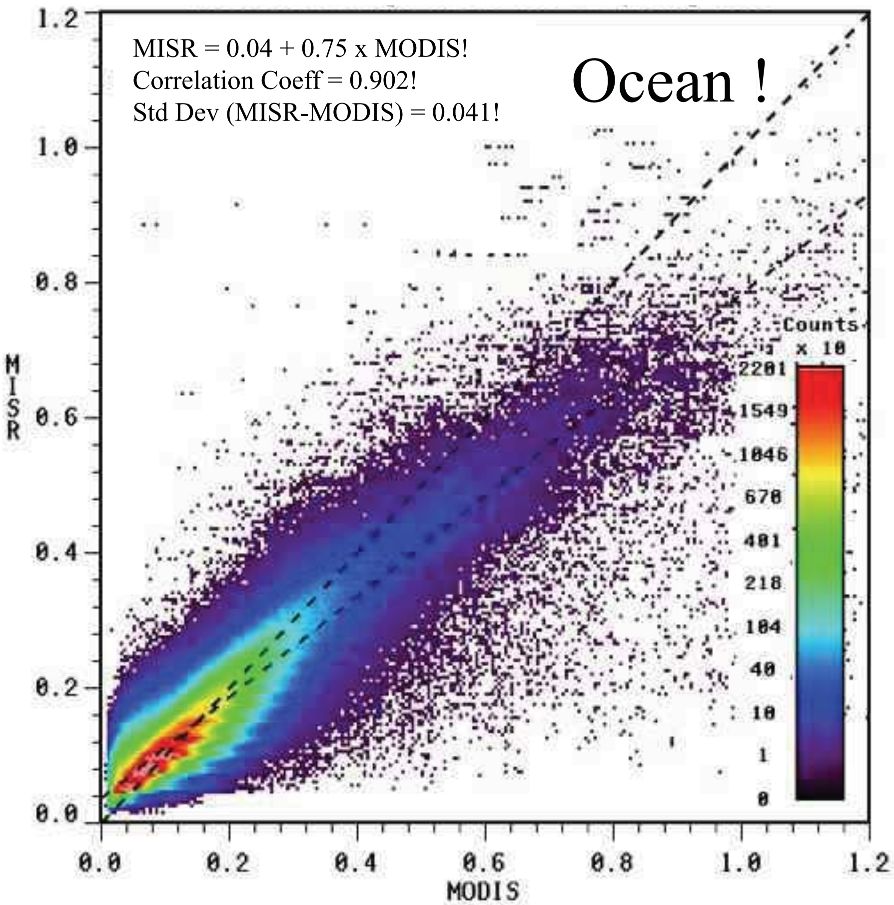


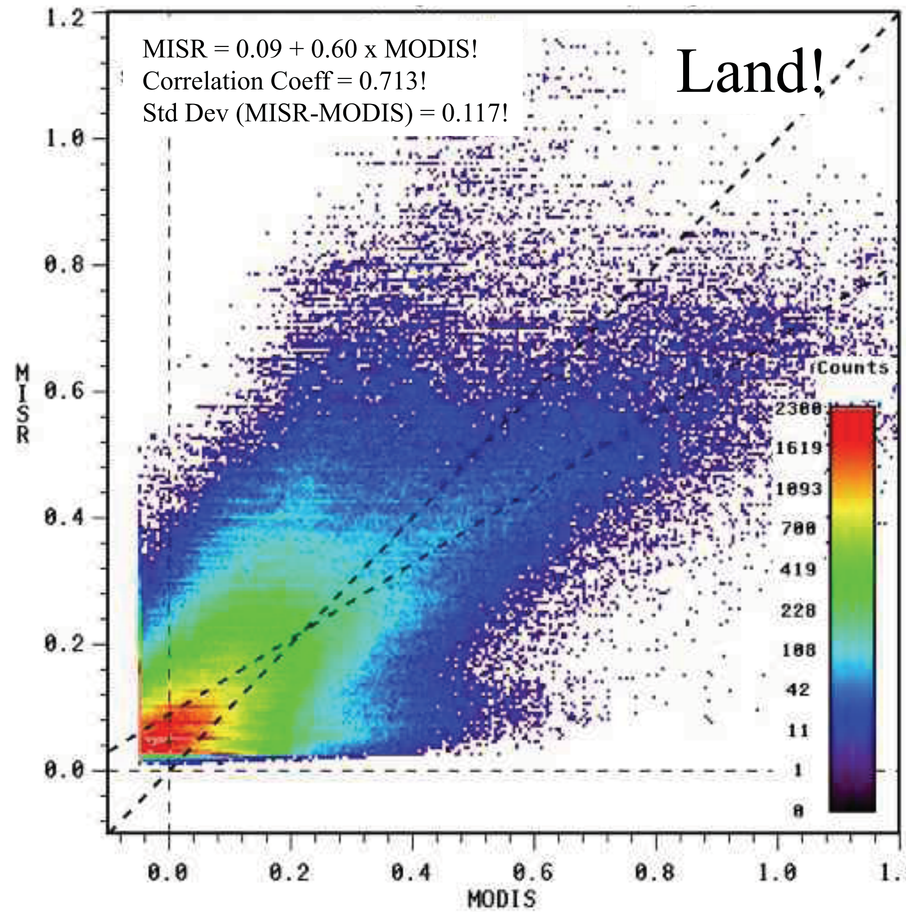
…includes bright desert dust source regions

MISR Team, JPL and GSFC

MISR-MODIS *Aerosol Optical Depth* Comparison

[MISR V22 vs. MODIS/Terra Collection 5; January 2006 Coincident Data]



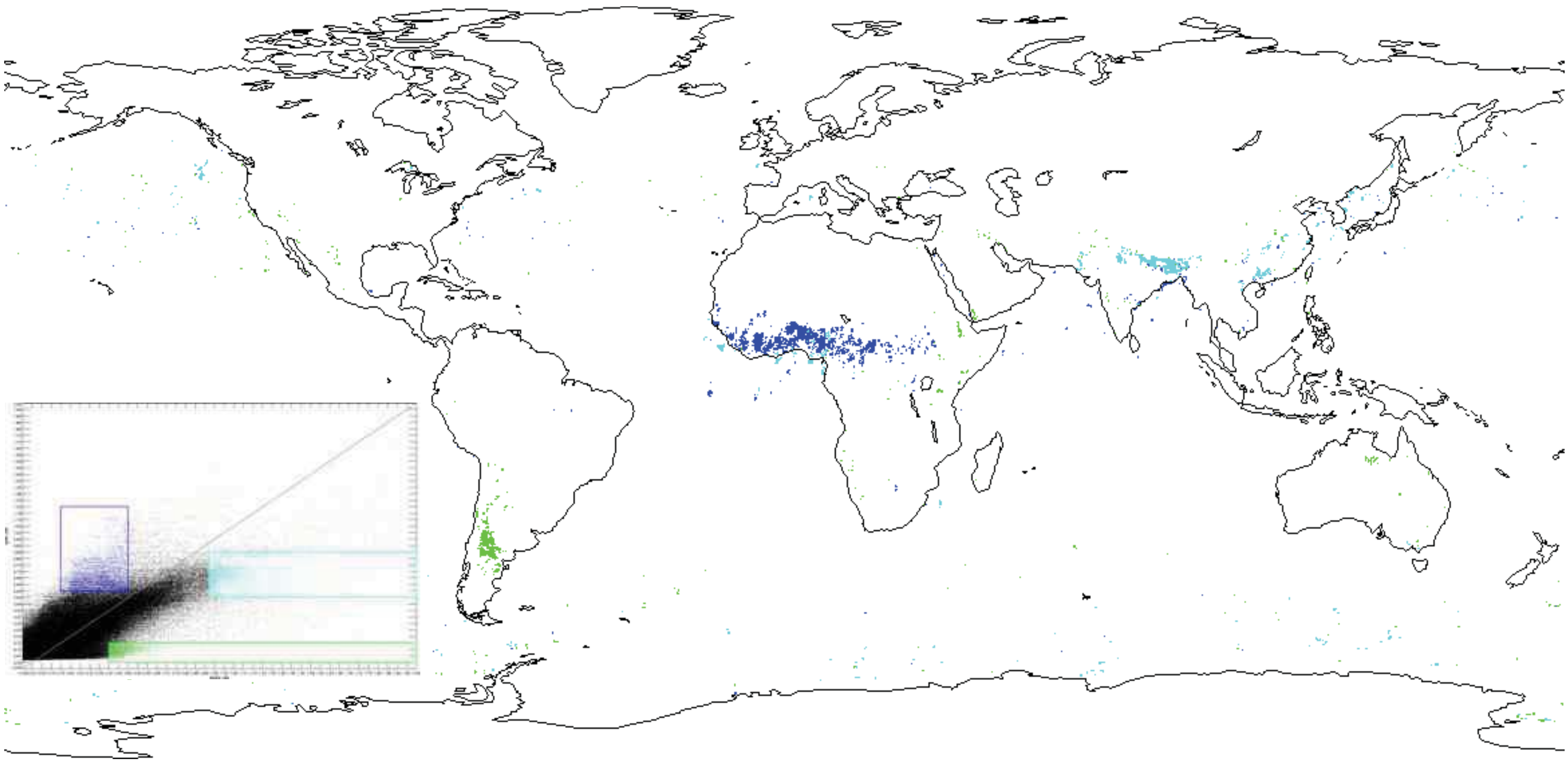


Over-ocean regression coefficient **0.90**
Regression line slope 0.75!
MODIS QC # 1!

Over-land regression coefficient **0.71**
Regression line slope 0.60!
MODIS QC = 3!

Kahn! Nelson, Garay et al., TGARS 2009

MISR-MODIS Coincident AOT ***Outlier Clusters!***



Dark Blue [MISR > MODIS] – N. Africa ***Mixed Dust & Smoke***
Cyan [MODIS > MISR, AOD large] – Indo-Gangetic Plain ***Dark Pollution Aerosol***
Green [MODIS >> MISR] – Patagonia and N. Australia ***MODIS Unscreened Bright Surface***

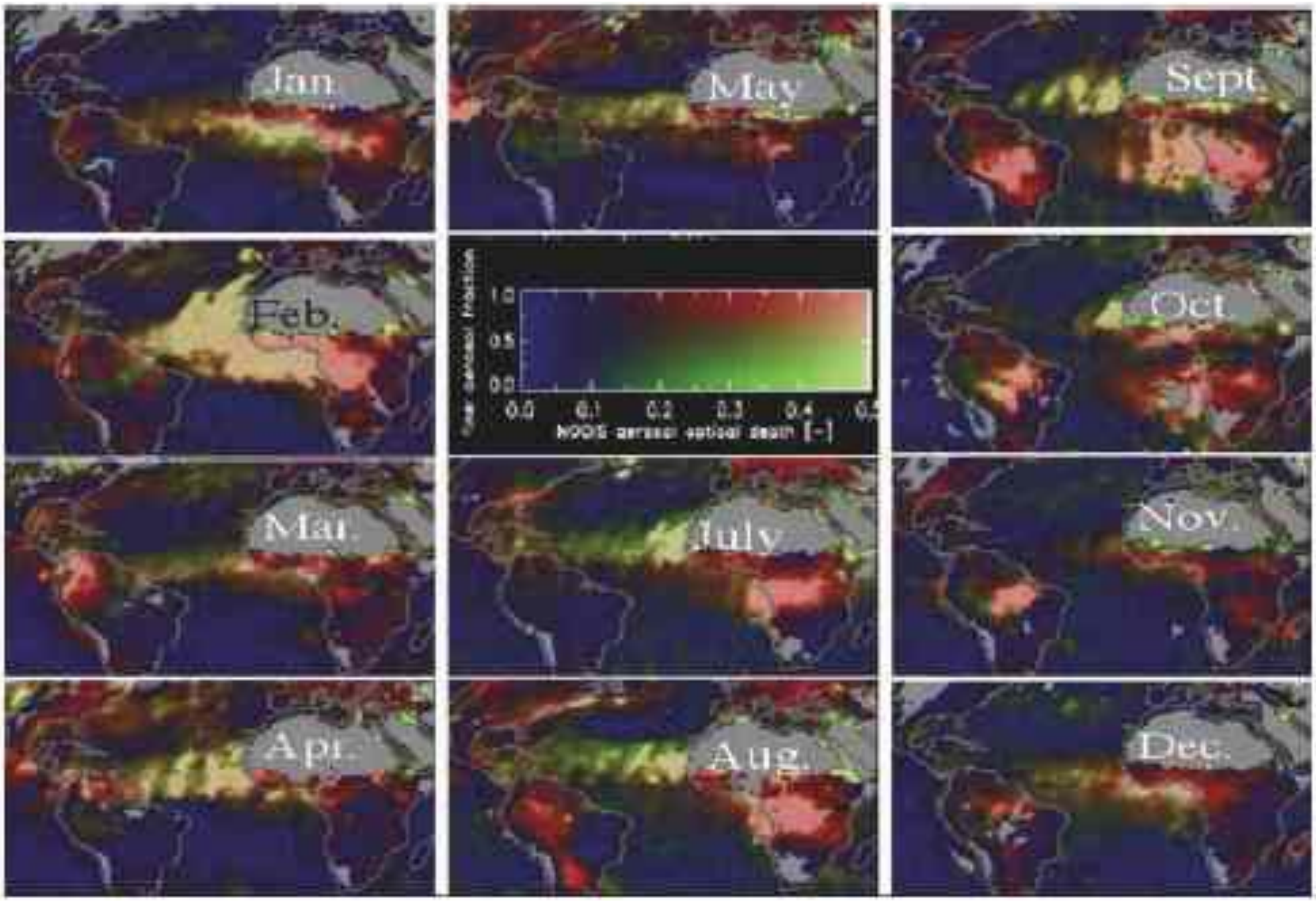
Kahn et al., TGARS 2009

Aerosol Retrievals –

Aerosol Microphysical Properties!

One MODIS *Aerosol Type* Classification:

Low AOT (blue), **High AOT+Coarse** (green), **High AOT+Fine** (red)



Kaufman et al., JGR, 2005

Los Alamos Fire, New Mexico May 9, 2000

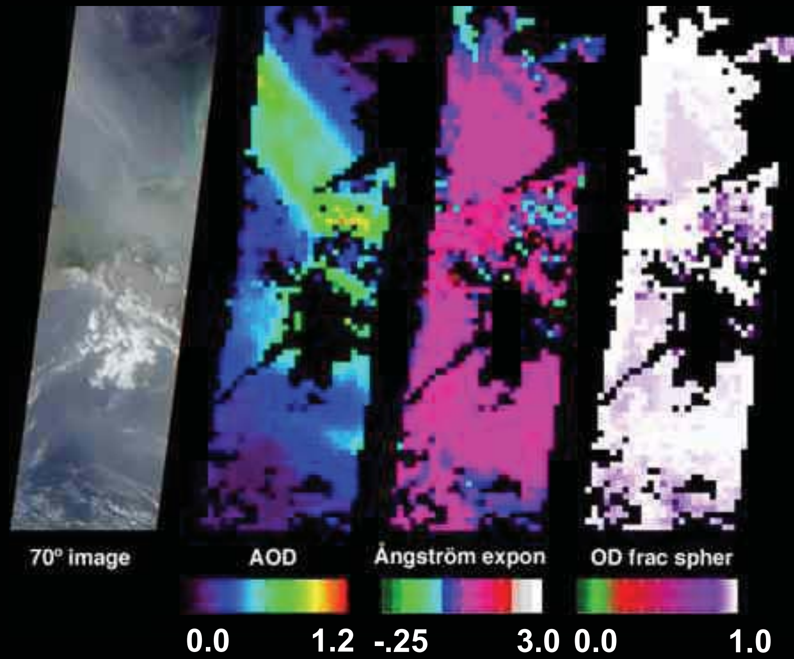
MISR 60˚ Forward!

MISR Nadir!

MISR 60˚ Aft

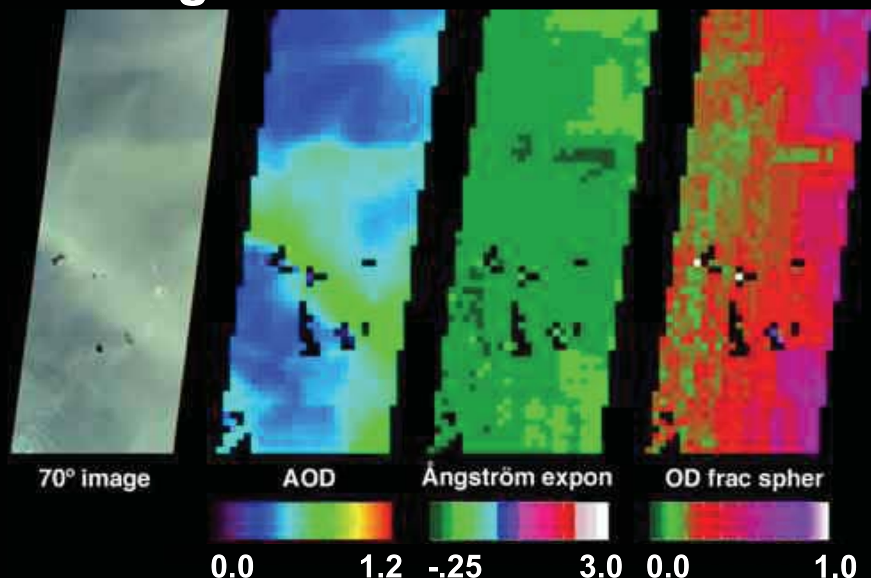
Smoke from Mexico -- 02 May 2002

Aerosol:!
Amount!
Size!
Shape



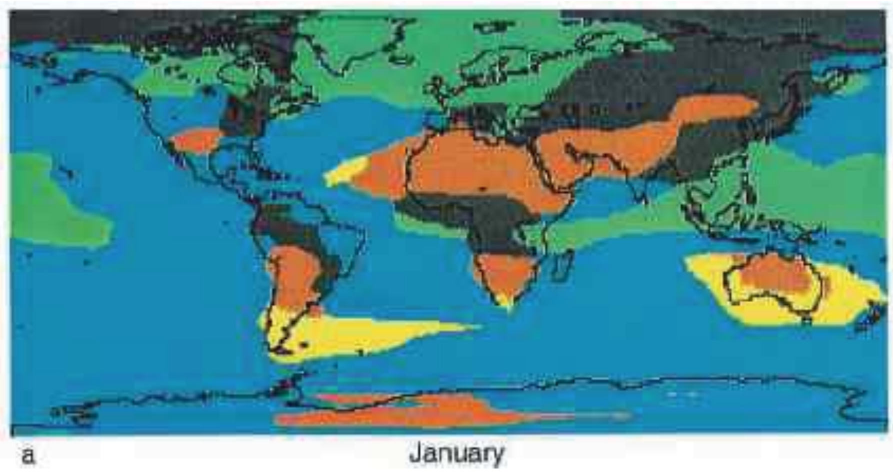
Medium!
Spherical!
Smoke!
Particles!

Dust blowing off the Sahara Desert -- 6 February 2004

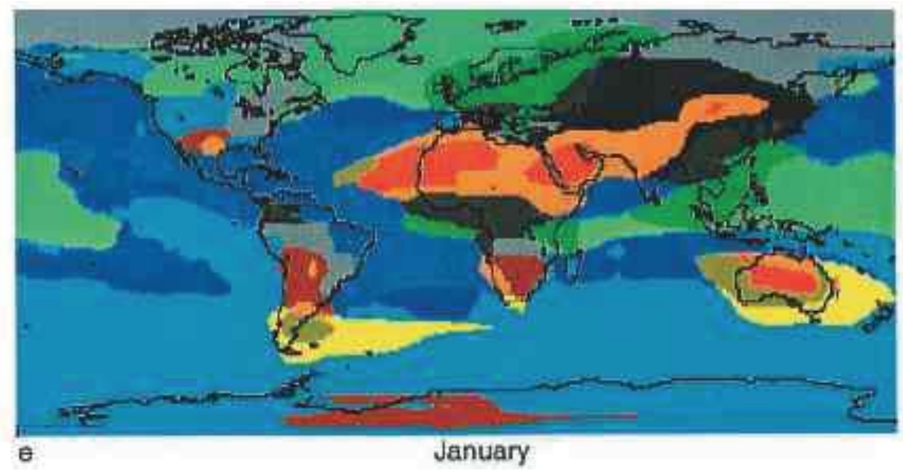


Large!
Non-Spherical!
Dust!
Particles!

With ***current*** technology, we are aiming for Regional-to-Global!
Aerosol Type Discrimination something like this…!



5 Groupings Based on Aerosol Properties!



13 Groupings Based on Aerosol Properties!

Global, **Monthly** Aerosol Maps Based on Expected MISR Sensitivity!
!
The examples shown here are simulated from aerosol transport model calculations…!

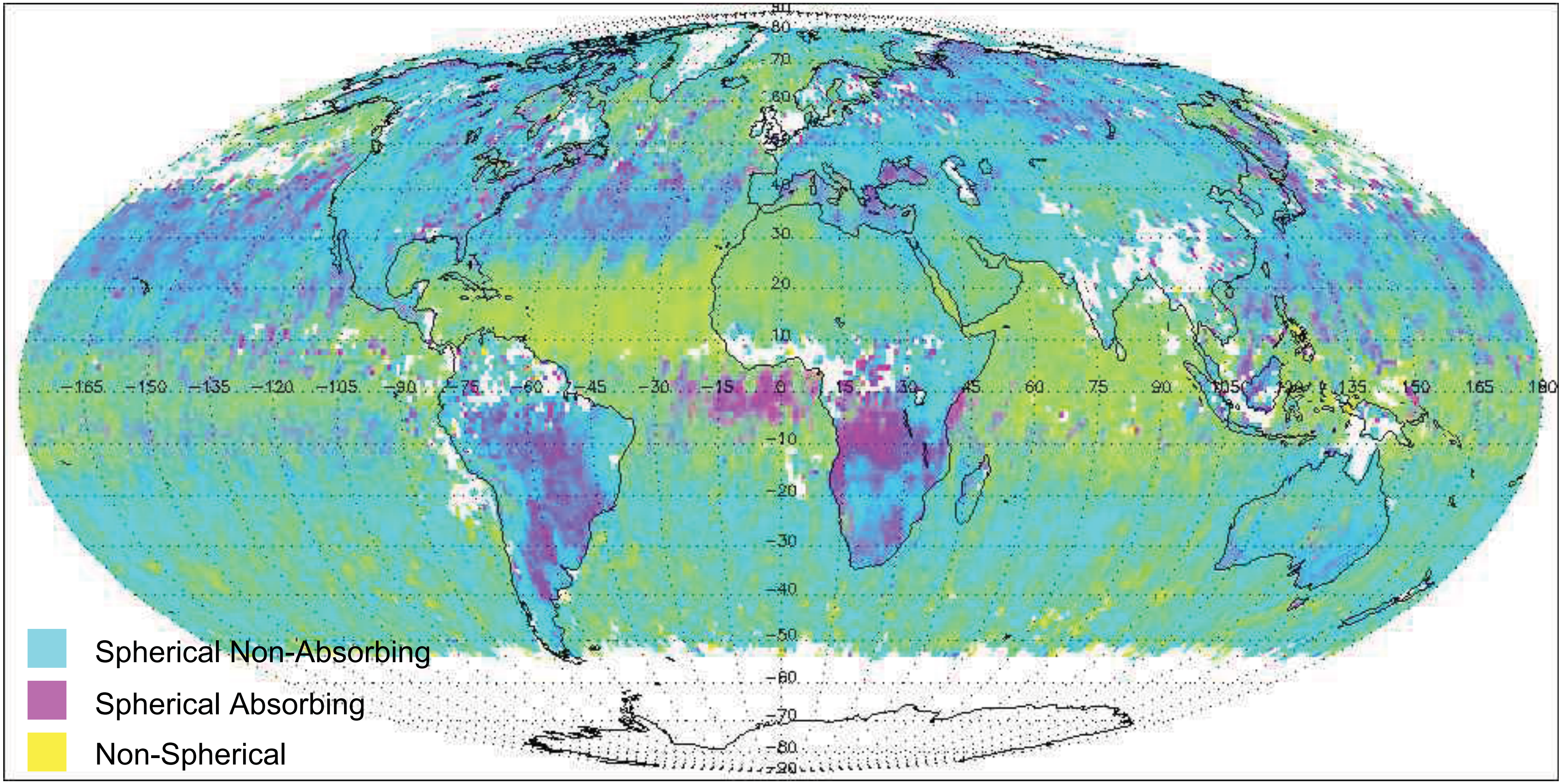
- With MISR – ***About a dozen*** ***Aerosol Air Mass type distinctions***, !
  based on 3-5 size bins, 2-4 bins based on SSA, and spherical vs. non!
- Sensitivity depends on conditions; ***AOD >~0.15*** needed, etc.!

→Adding ***NIR & UV*** wavelengths, ***Polarization*** should increase this capability !

Kahn et al., JGR 2001!

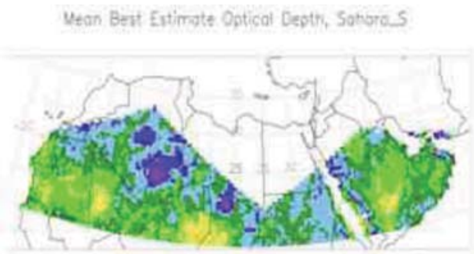
MISR *Aerosol Type* Distribution

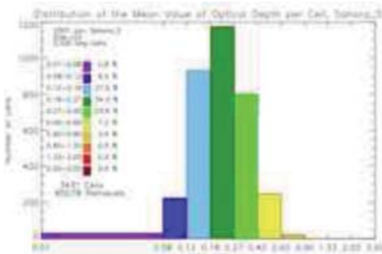
MISR Version 22, July 2007

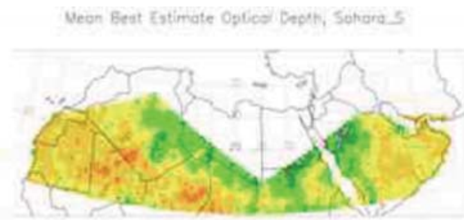


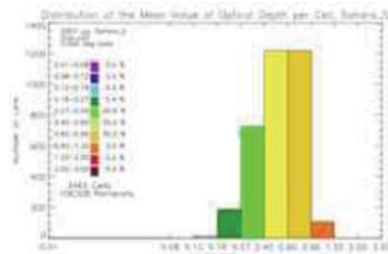
Kahn, Gaitley, Garay, et al., JGR 2010

Steps Toward MISR Standard Product *Aerosol-Type Quality Flag*!









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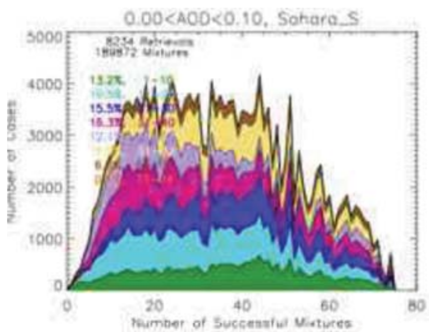
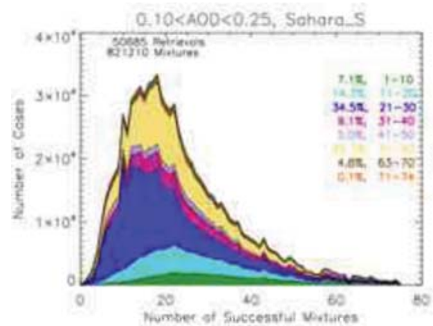
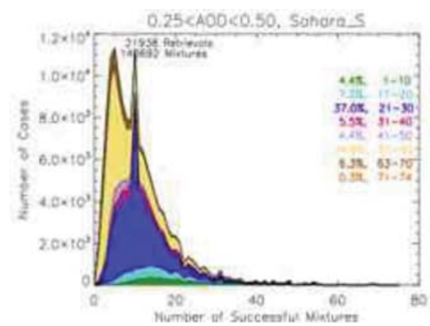
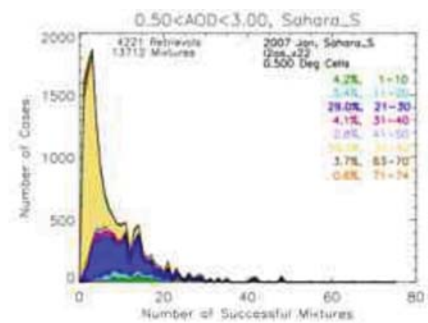
!36/%&' ( )%$%" * "+"%- . %/01+/2345#%









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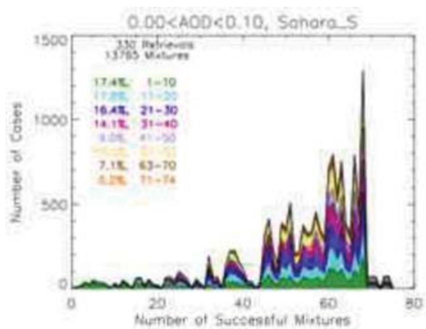

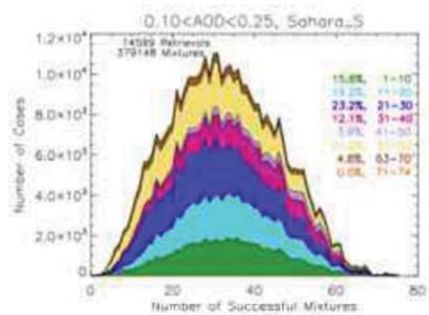

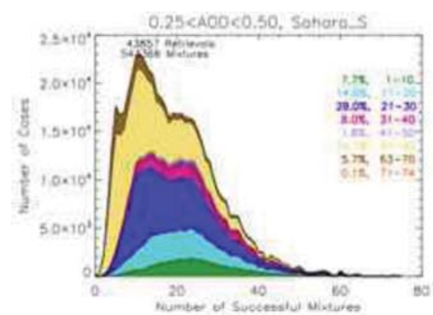

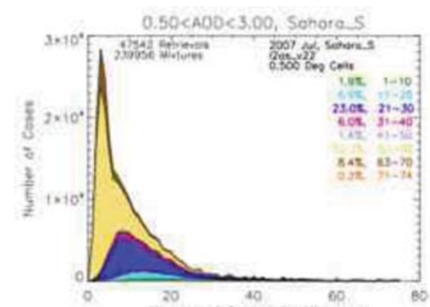

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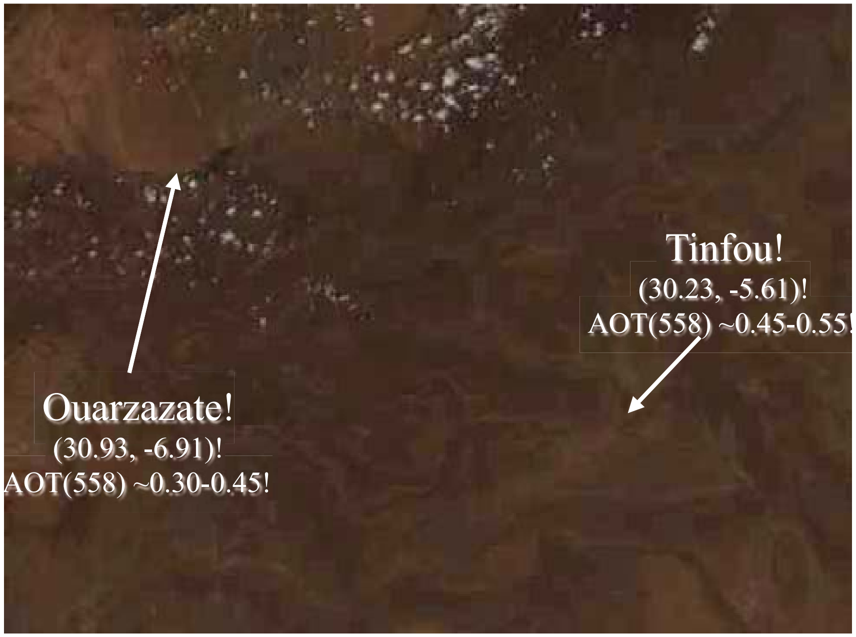
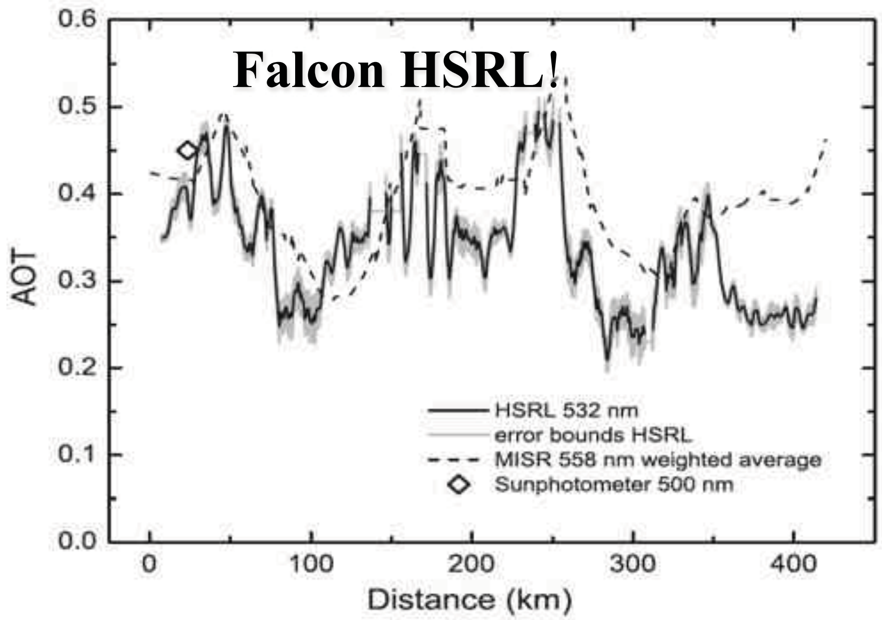
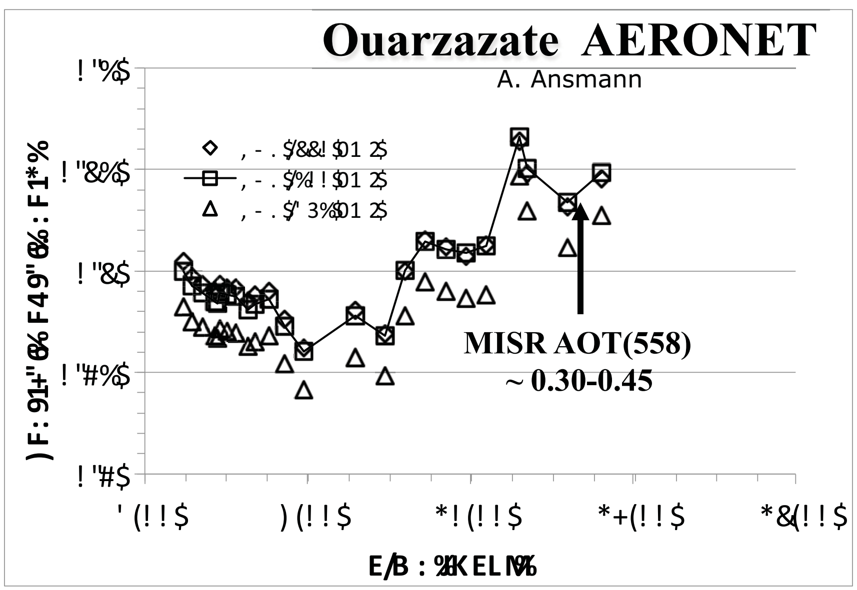
… because aerosol Type is much more sensitive to retrieval conditions than AOD

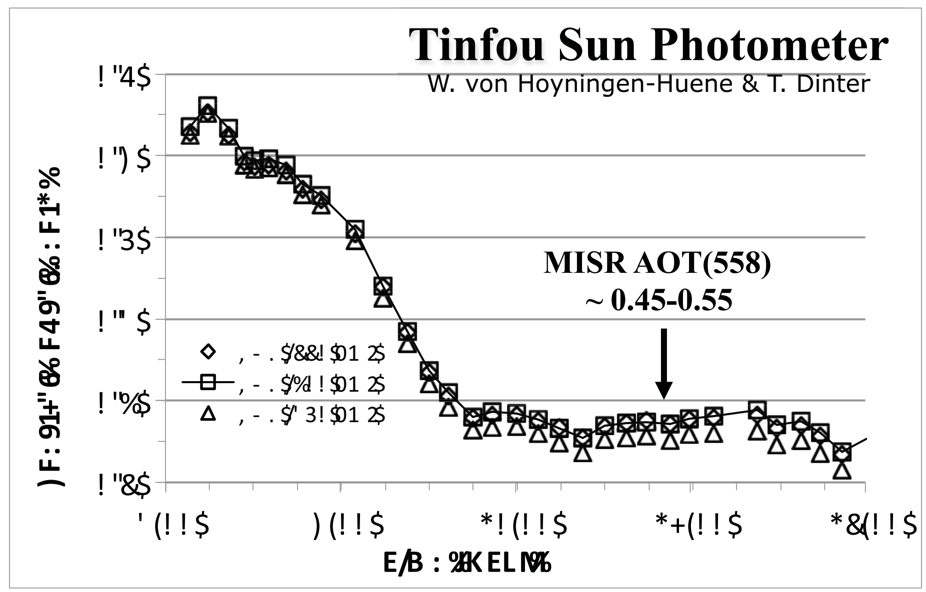
Kahn, Gaitley et al., in preparation

SAMUM Campaign Morocco – June 04, 2006

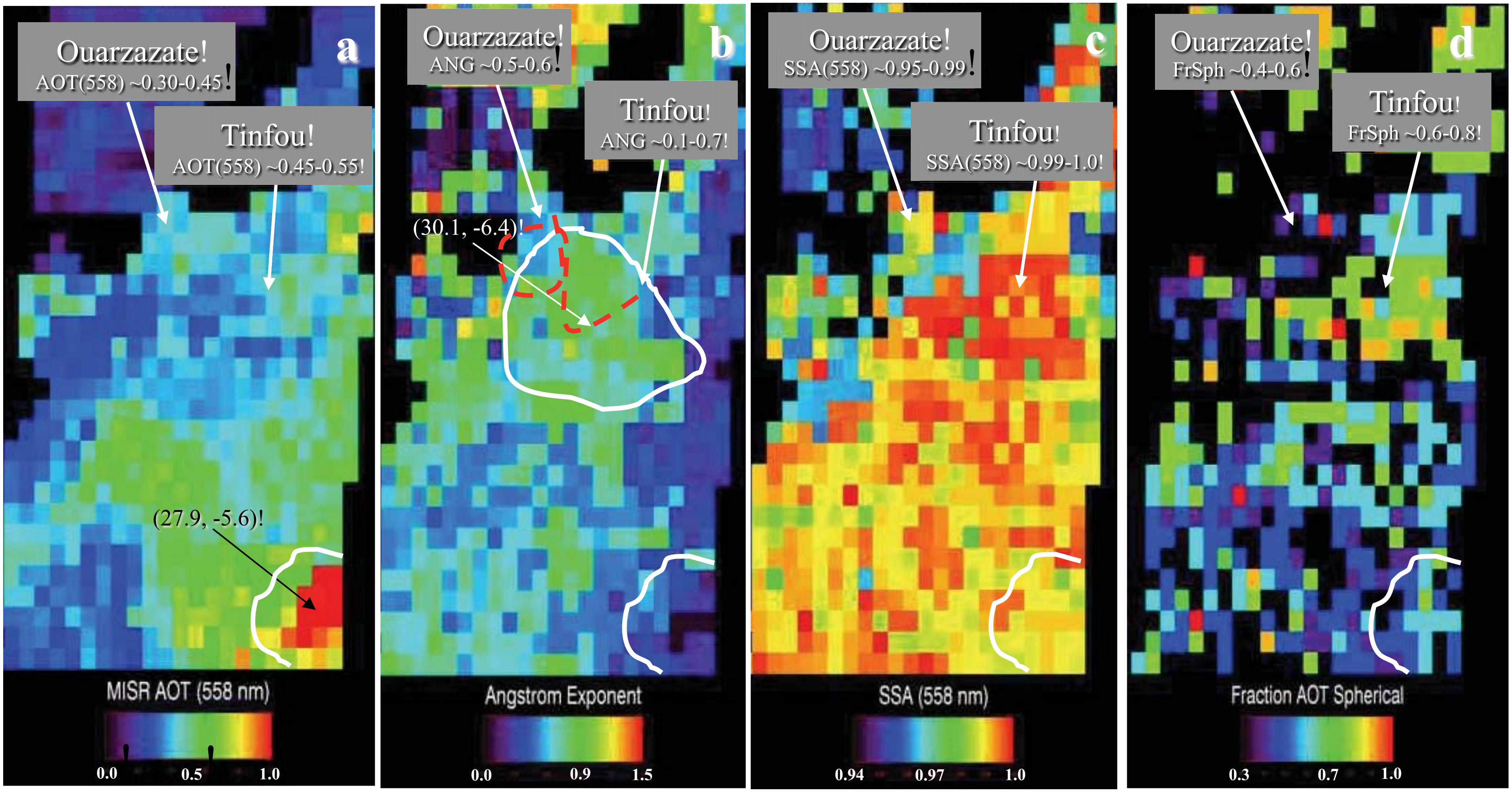








MISR SAMUM Aerosol Air Masses (V19) - June 04, 2006
Orbit 34369, Path 201, Blocks 65-68, 11:11 UTC



- A **dust-laden density flow in the SE** corner of the MISR swath
- **High SSA, ANG** & **Fraction Spherical** region SE of Ouarzazate, includes Zagora!

Kahn et al., Tellus 2009!

MISR Aerosol V22 Algorithm Upgrade Priorities
Supporting Dust, Smoke, & Aerosol Pollution Applications

- Based on ***10 Years of Validation*** Data!

-- ***Low-light-level*** gap & quantization noise!

-- ***High-AOD underestimation*** of AOD (*missing **low-SSA** particles; algorithm issues*)!

-- Missing ***Medium-mode*** particles ($r_{eff} \sim 0.57, 1.28$ µm)!

-- More spherical, ***absorbing particles*** (*SSA* ~ 0.94, 0.84, maybe 0.74)!

-- ***Mixtures of smoke & dust*** analogs; more ***Bi- and Tri-modal*** spherical mixtures!

-- ***Flag*** indicating when there is insufficient sensitivity for ***particle property*** retrieval!
(possibly different retrieval path under this condition)!

-- Lack of a good ***Coarse-mode Dust Optical Analog*** remains an issue!

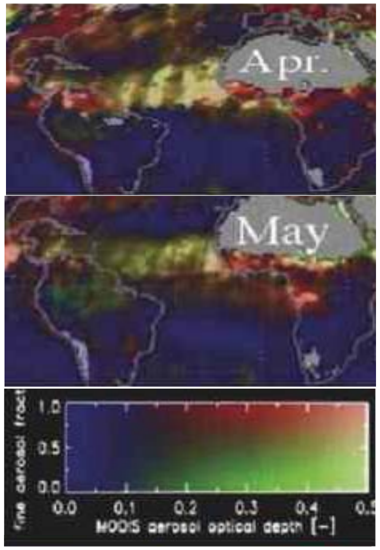
Kahn, Gaitley, Garay, et al., JGR 2010

Applications –

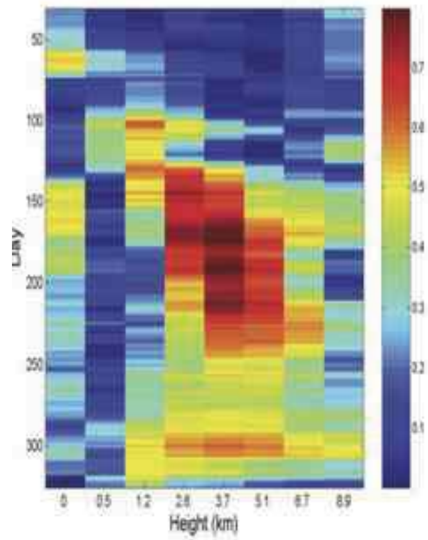
Types, Plume Heights, & Transports

Dust, Smoke, Volcanic Ash

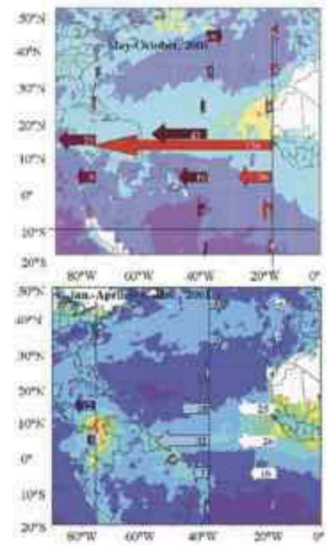
Aerosol Material Fluxes: Atlantic Dust & Asian Pollution



MODIS AOD & Type
Low AOD, Fine BioBurn, Coarse Dust

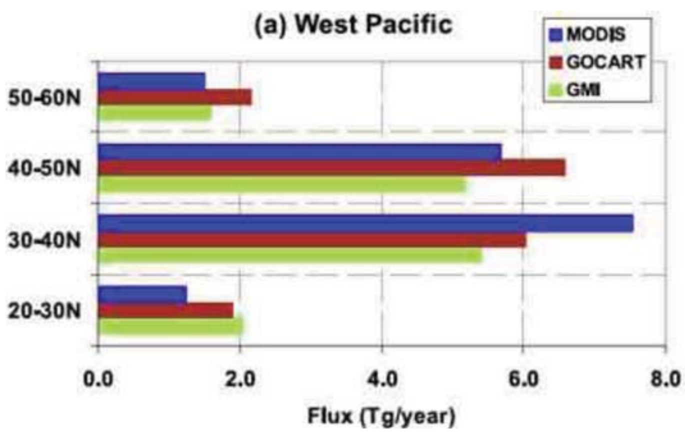


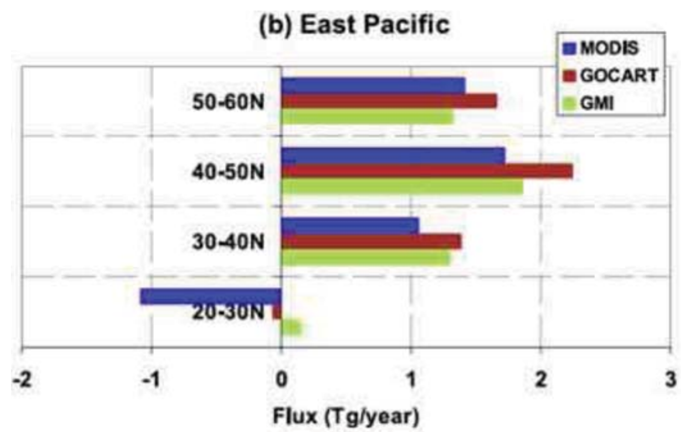
NCEP W Wind - MODIS AOD
Correlation 2.6-5 km; May-October



Dust Transport Estimate (Tg)
May-October (Top) January-April (Bot)

Kaufman et al., JGR 2005

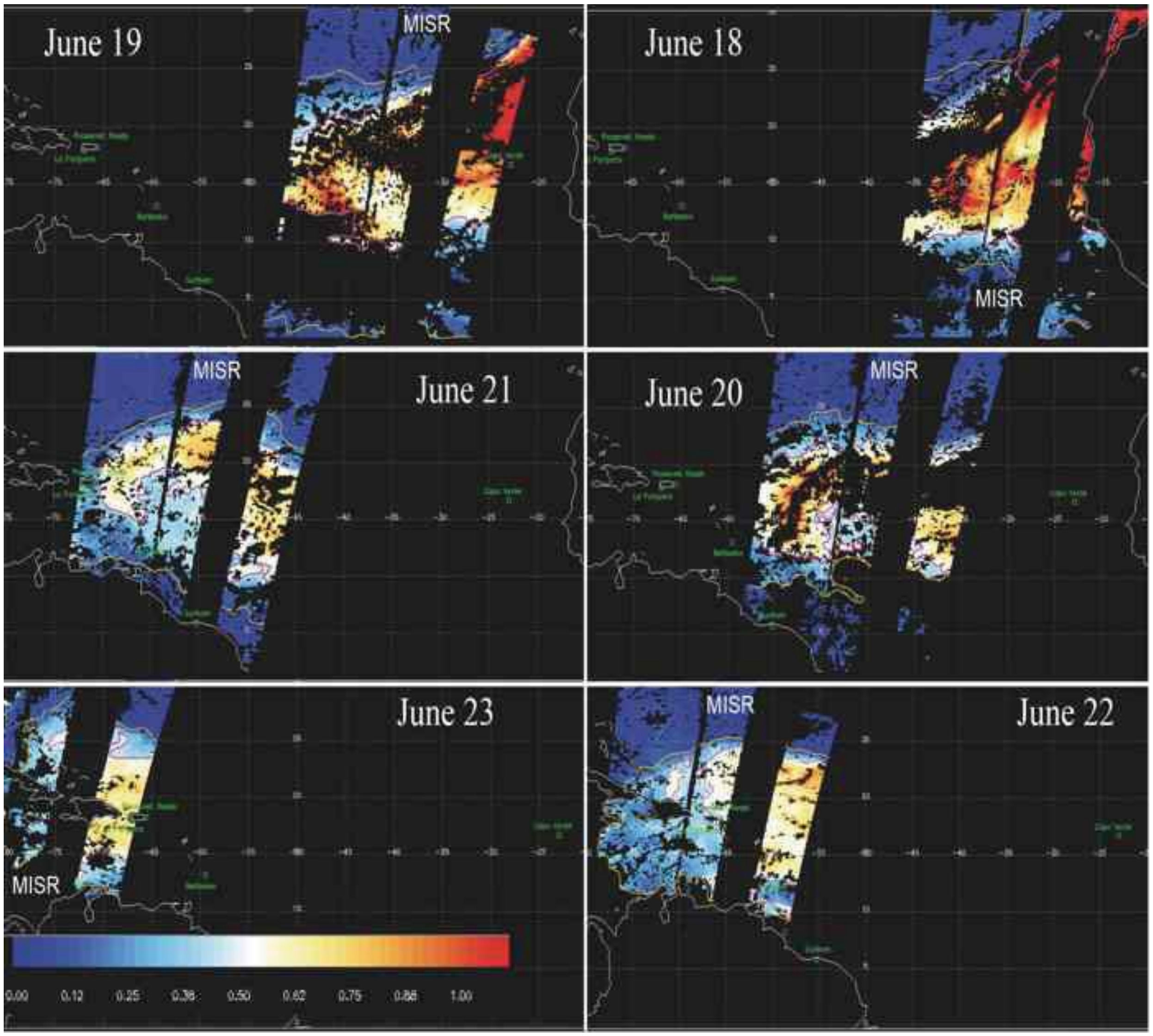




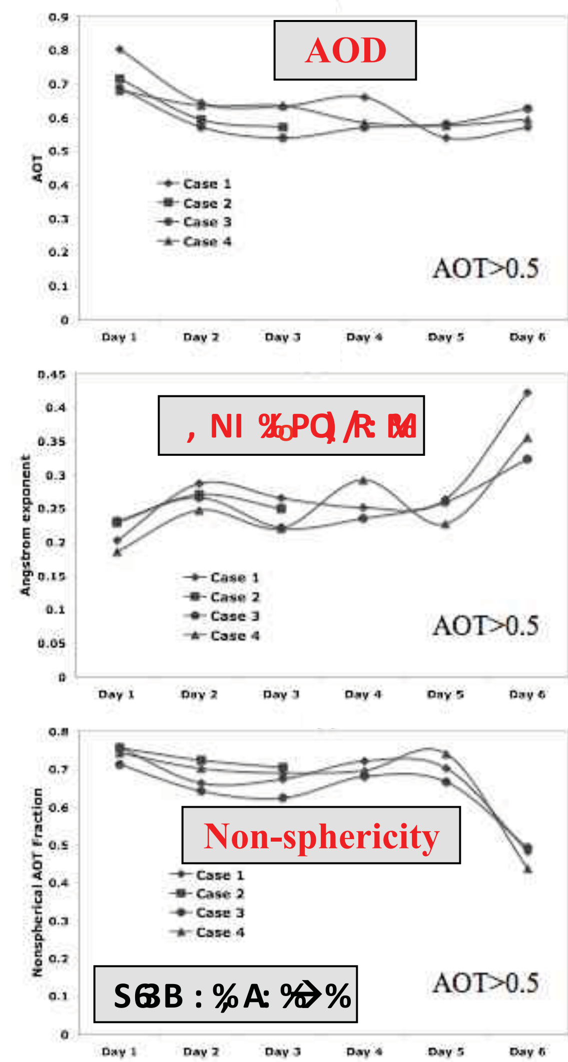
MODIS AOD & type, Field Campaign aerosol properties & vertical distribution, GEOS model winds;
Compared with GOCART and GMI model Fine-particle mass fluxes! *Yu et al., JGR 2008*

Constraining Aerosol Sources, Transports, & Sinks

Complementary MISR & MODIS AOD; Saharan Dust Plume over Atlantic June 19-23, 2000



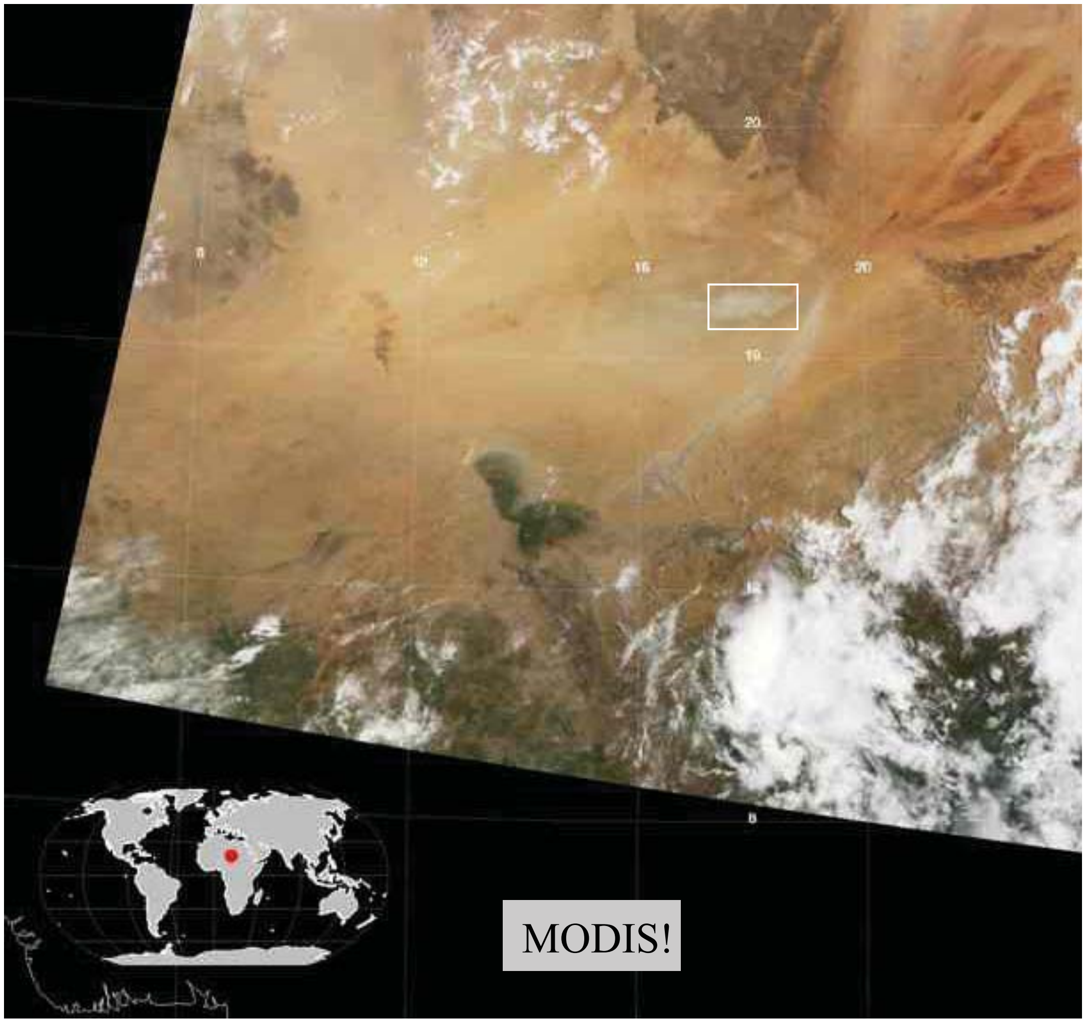
Contours: AOT=0.15 (yellow); AOT=0.5 (purple)

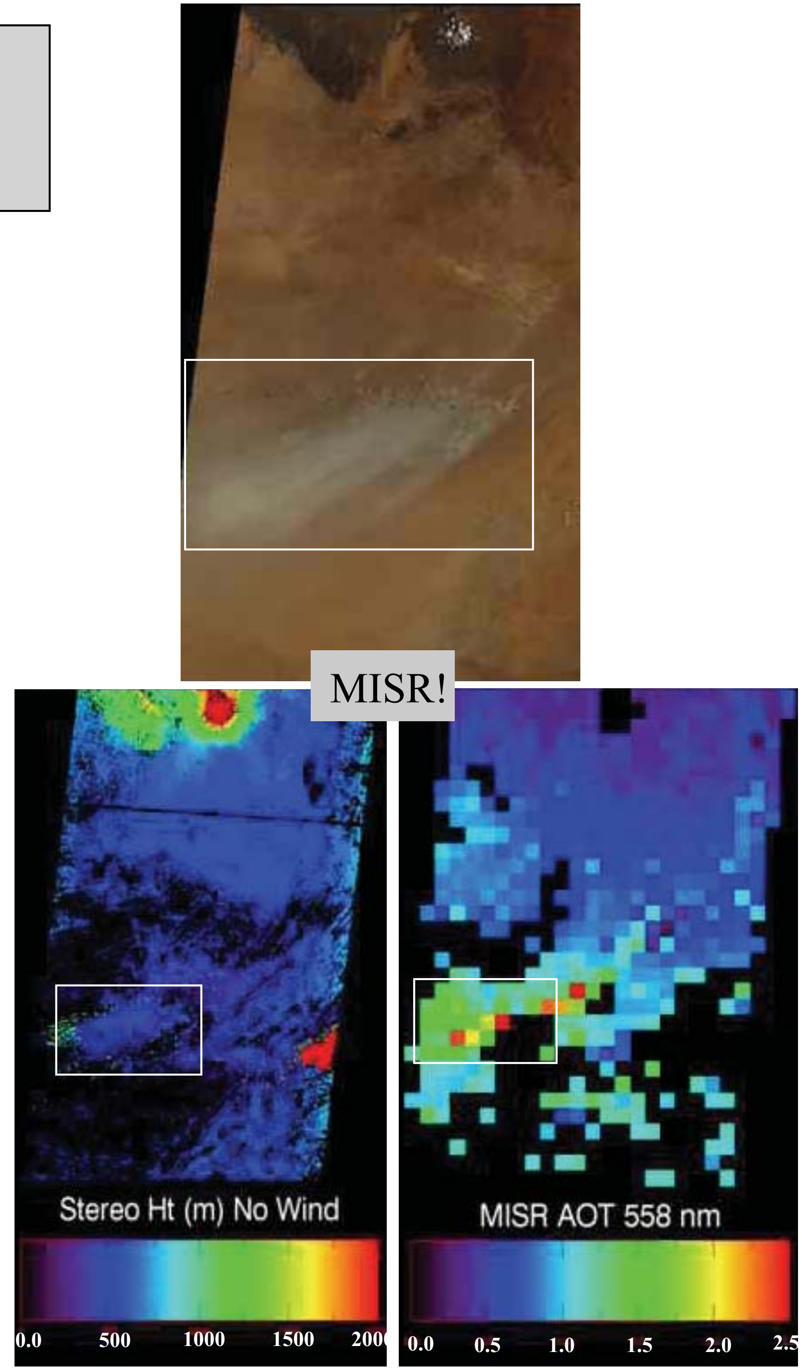


Kalashnikova and Kahn, JGR 2008

Saharan Dust Source Plume

Bodele Depression **Chad June 3, 2005 Orbit 29038**



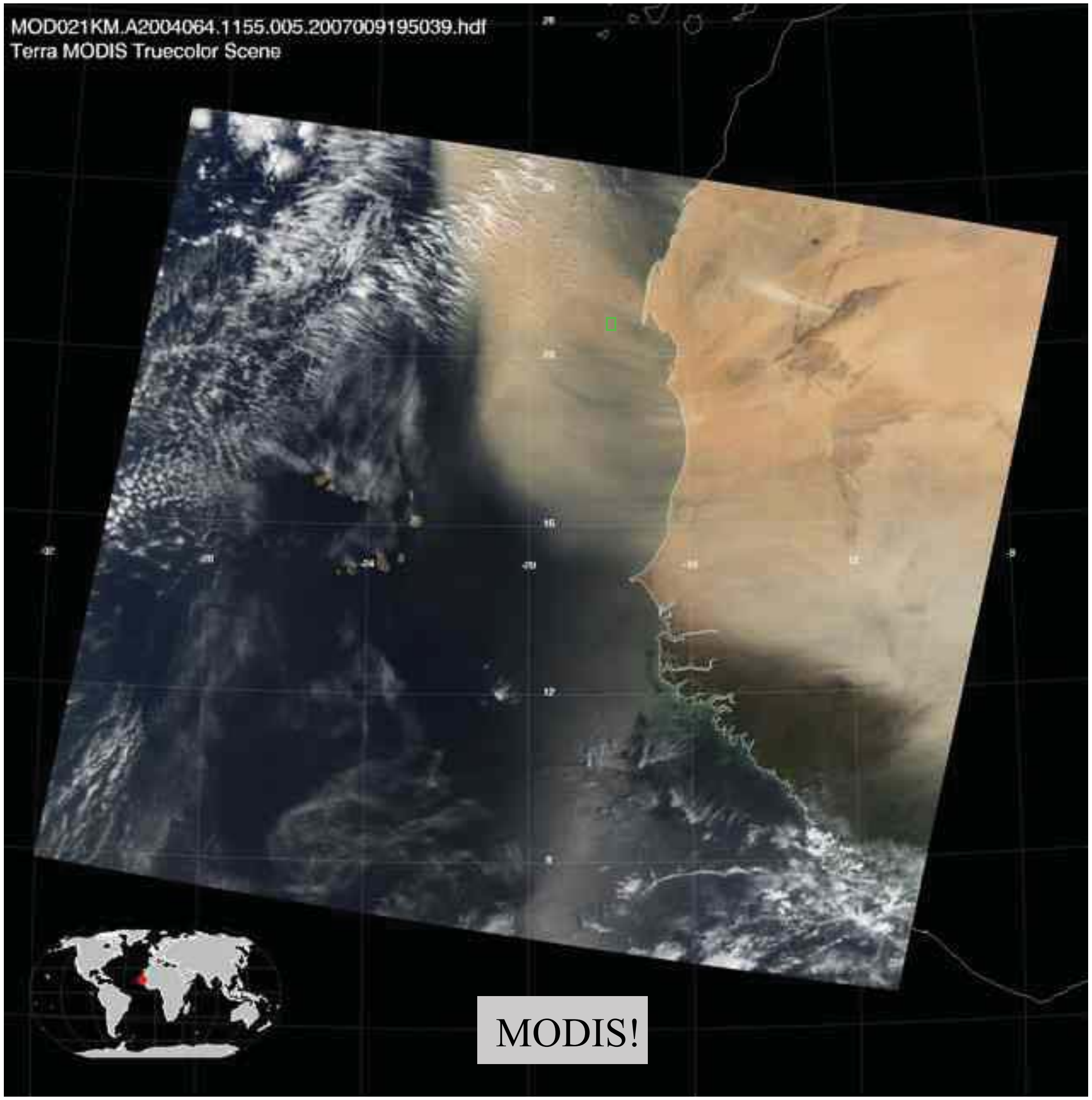


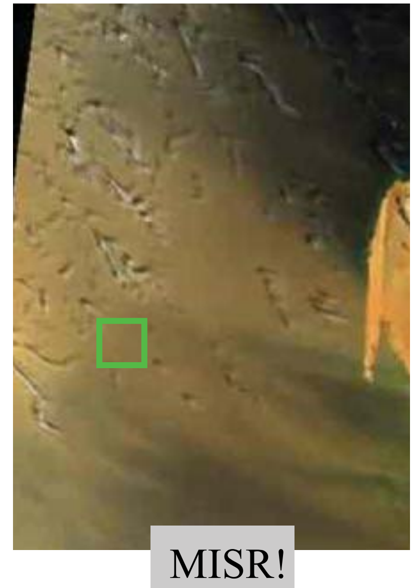
Dust is injected near-surface…!

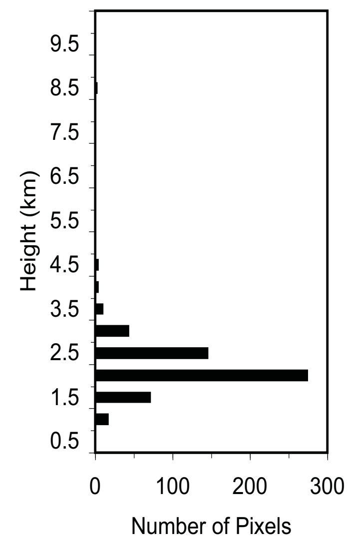
Kahn et al., JGR 2007!

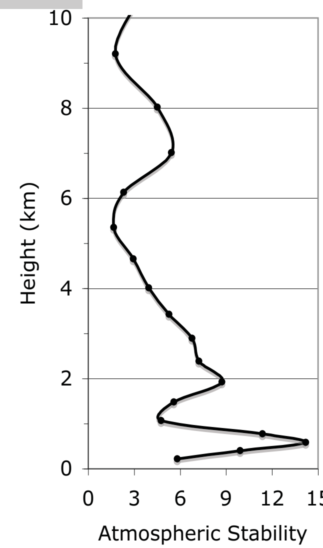
Transported Dust Plume

Atlantic, off Mauritania March 4, 2004 Orbit 22399





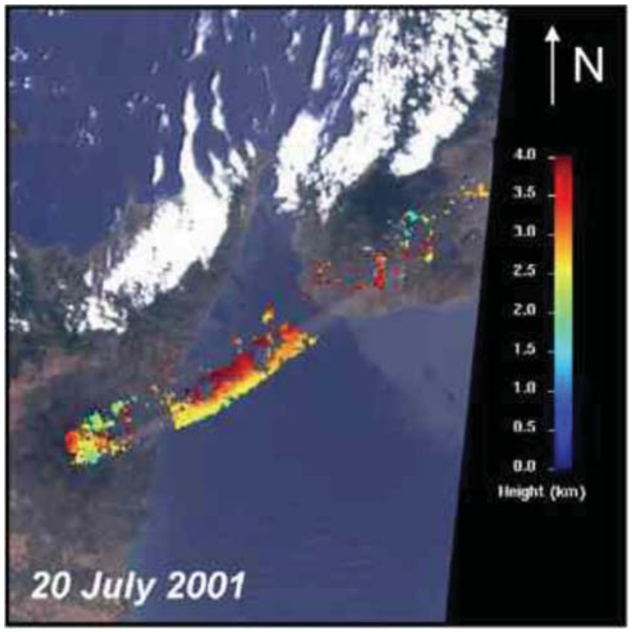




Transported dust finds elevated layer of relative stability… ! *Kahn et al*., JGR 2007!

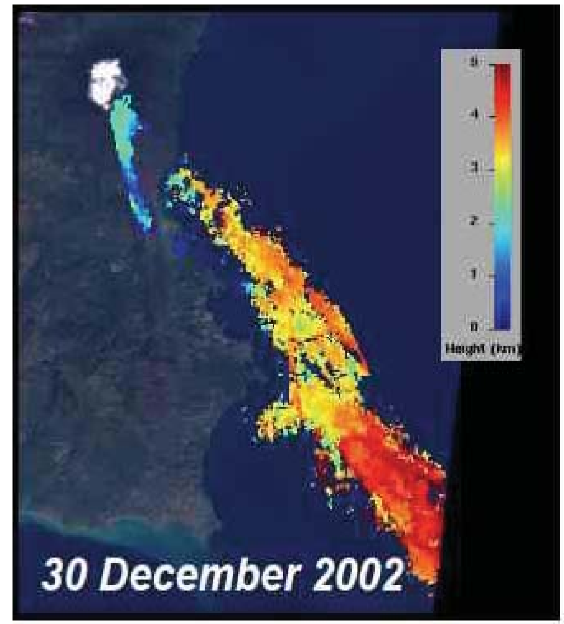
Mount Etna Plume Height and Eruption Style from MISR

!"#$#%&'&') '&+, -%& '/'&0 1$2#- %& '&4#$51$6%& '7& 6 18%& '7&9+8+: %&-; &'7&1+$= >5#$*
< 1) G%520: +H'45#0%;%1#"%E6 9"#/9%63B : 0'*&7&9 1#?, : 2'&12'$+! *+$*



MISR nadir-viewing, true-color image showing Etna, with stereo-derived plume height superposed

29 Sept. 2006 – MISR retrieved mostly small spherical particles, indicating a sulfate/water-dominated plume



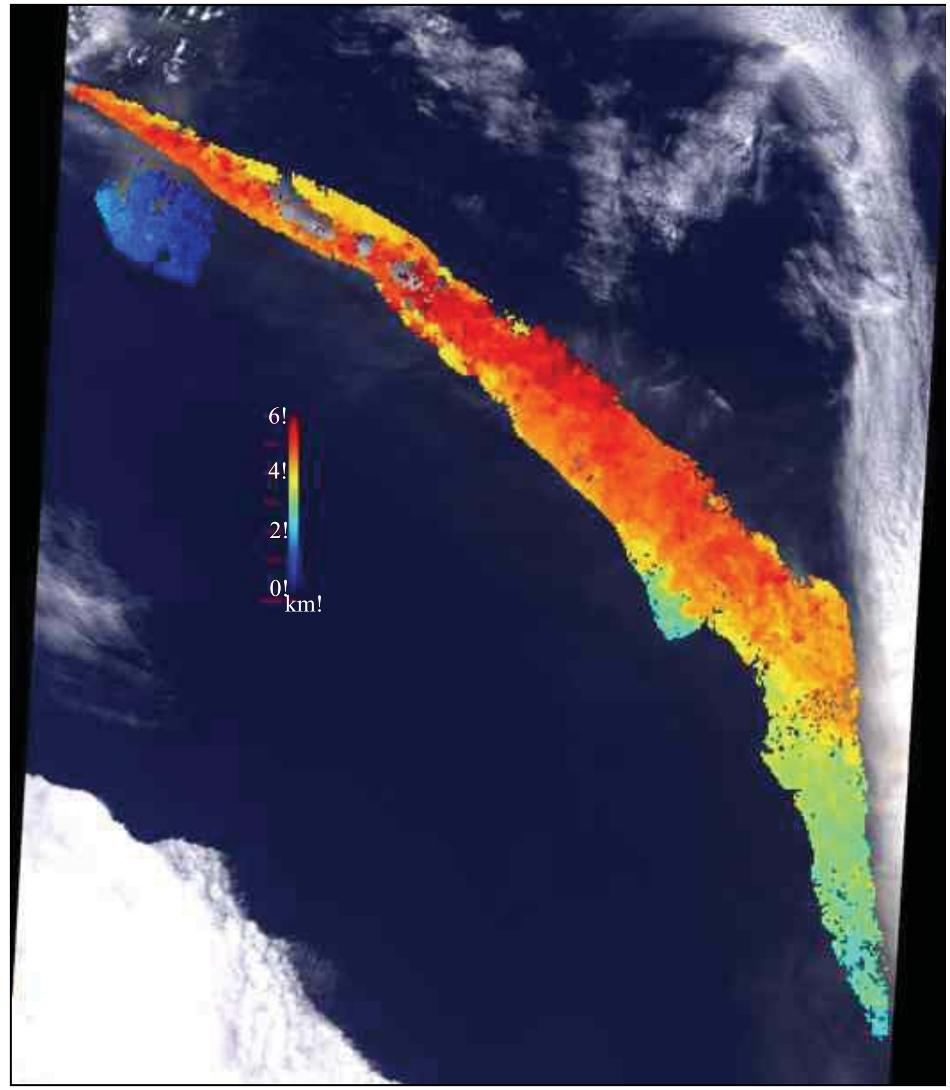
MISR stereo heights for the ash-dominated plume on 30 December 2002

Indications of Eruption Strength:!

- ***Plume Height*** from MISR stereo imaging!
- ***Ash to Sulfate/Water particle AOD ratio*** from MISR-retrieved particle shape and size!

MISR Stereo-Derived Plume Heights

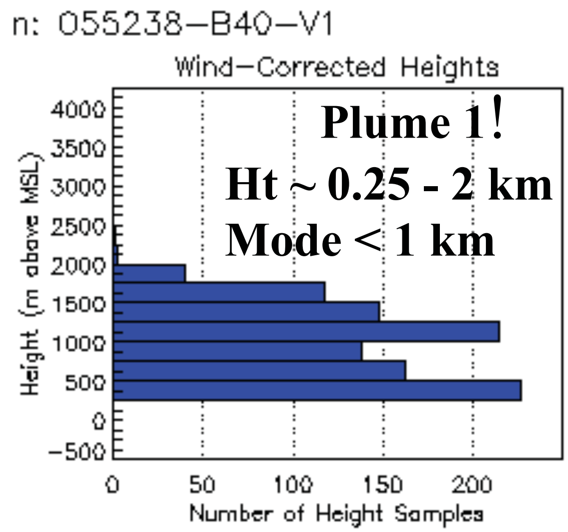
07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39



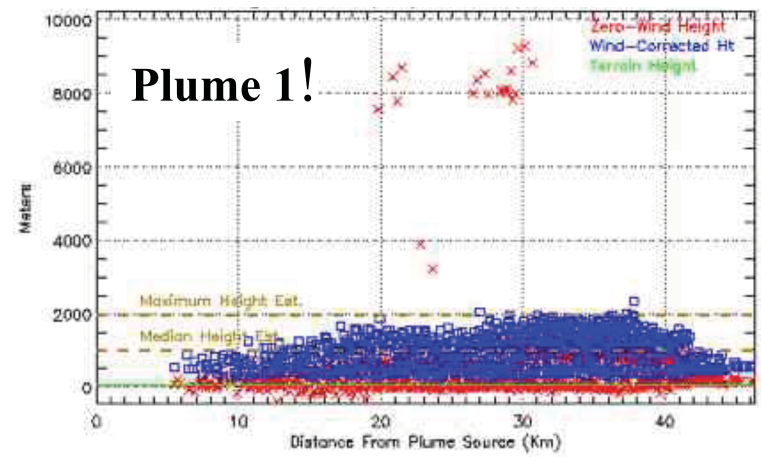
D. Nelson and the MISR Team, JPL and GSFC

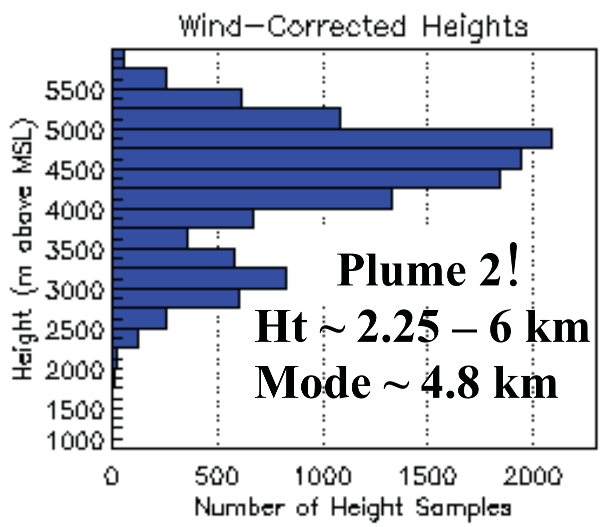
MISR Stereo-Derived Plume Heights

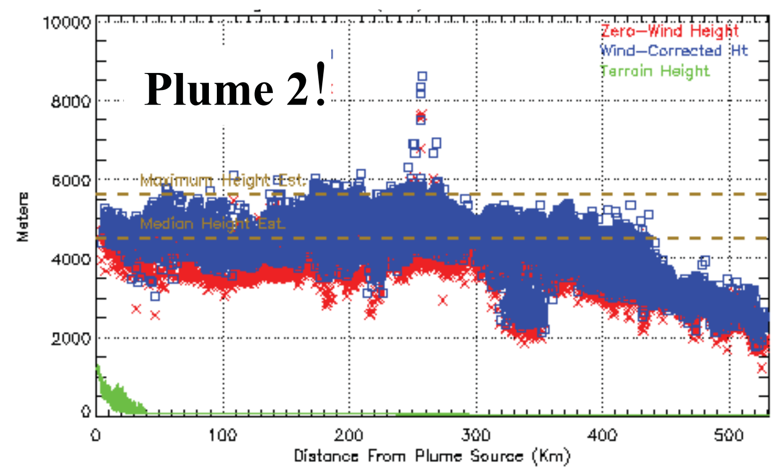
07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39



Height: Blue = Wind-corrected



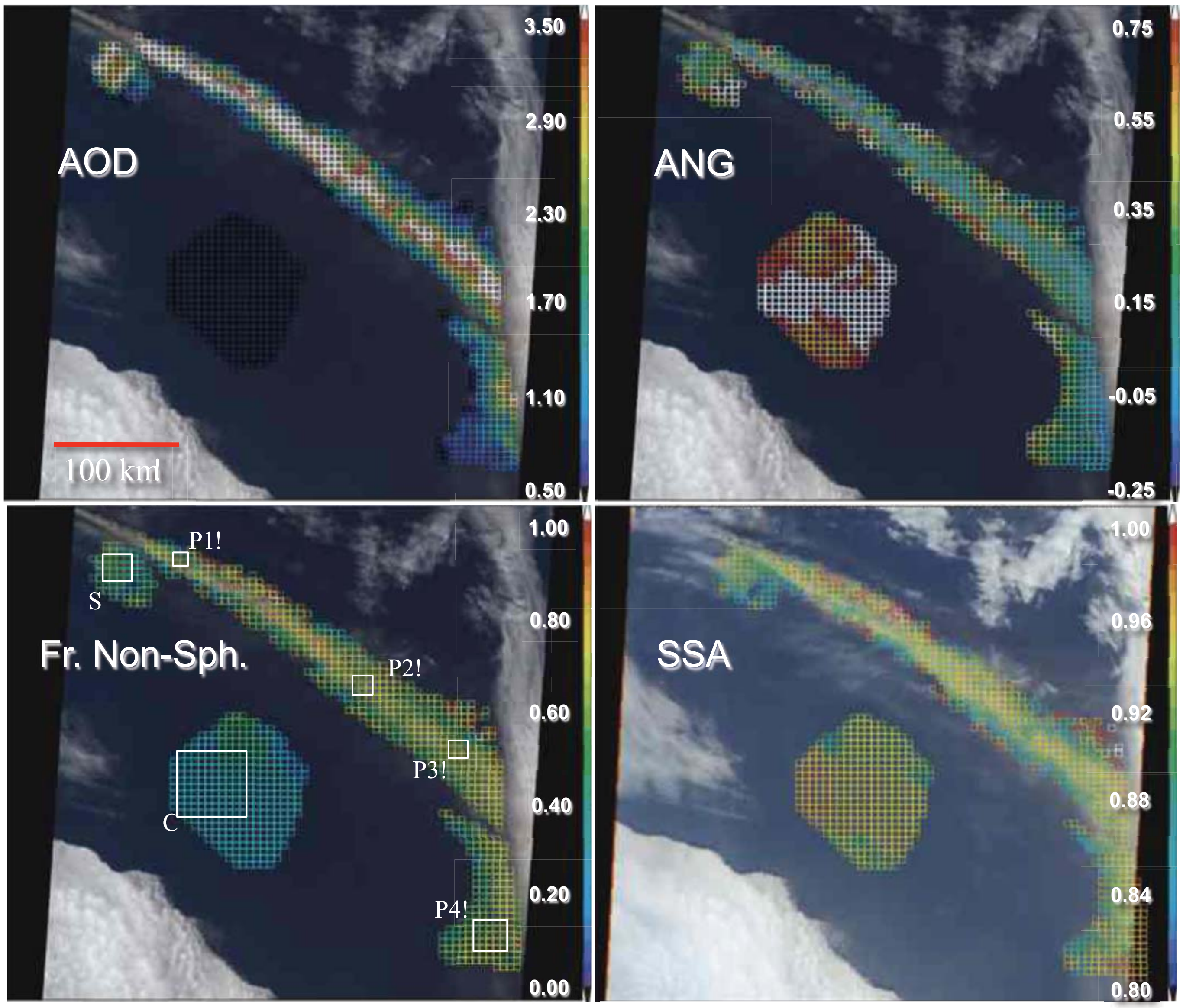




D. Nelson and the MISR Team

MISR Research Aerosol Retrievals

07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39

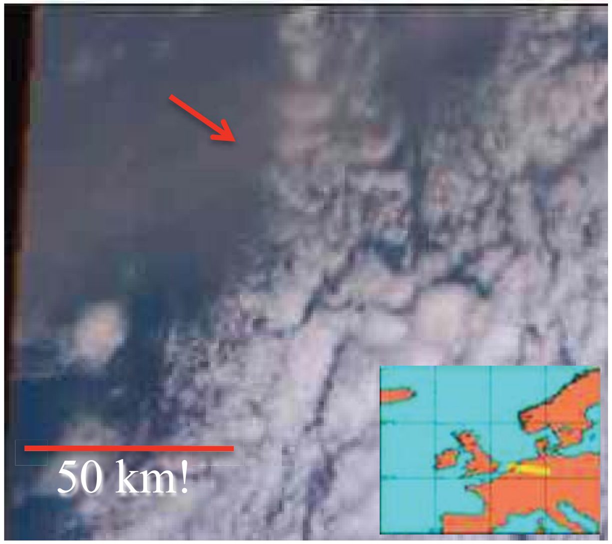


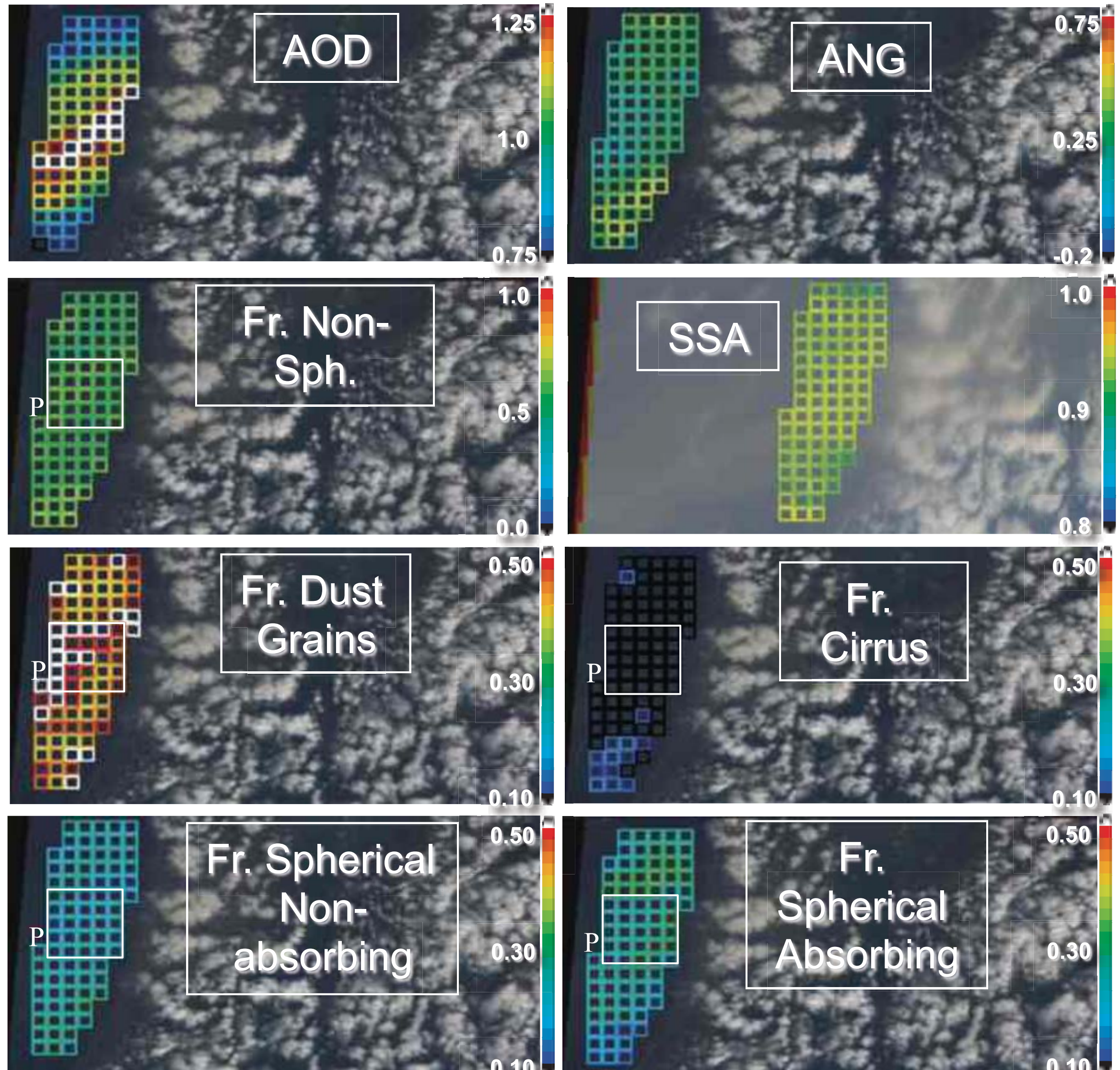
Plume Particles

- Distinct from background!
  - -- ***larger***, ***darker*** !
  - -- ***much higher AOD***
- ***Non-spherical*** dominated!
- Brighten downwind!
- Tend to decrease in size! downwind!

Kahn & Limbacher, ACP 2012

*MISR Research **Aerosol Retrievals***
***16 April 2010** Orbit 54931 Path 197 Blk 49 UT 10:45*

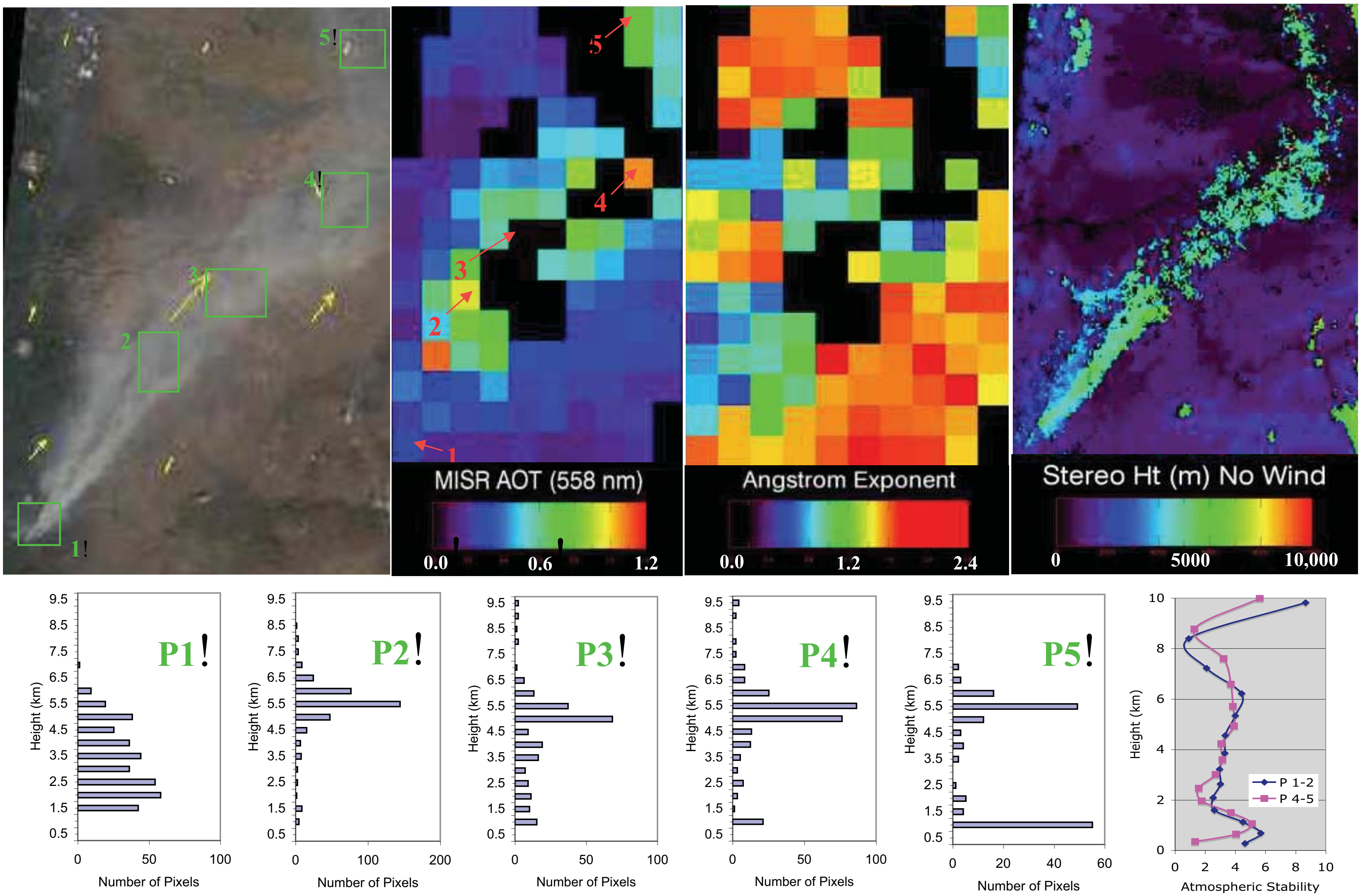




- ***1-2 days downwind*** of !
  Iceland volcano source!
- Distinctly ***high AOD***
  (peak >1.25)!
- Retrieved ~50% AOD !
  non-spherical dust grains!
- ***Medium*** particles ~ no "cirrus" !
- Model ***back-trajectory needed***!
  to identify plume confidently!

Kahn & Limbacher, ACP 2012

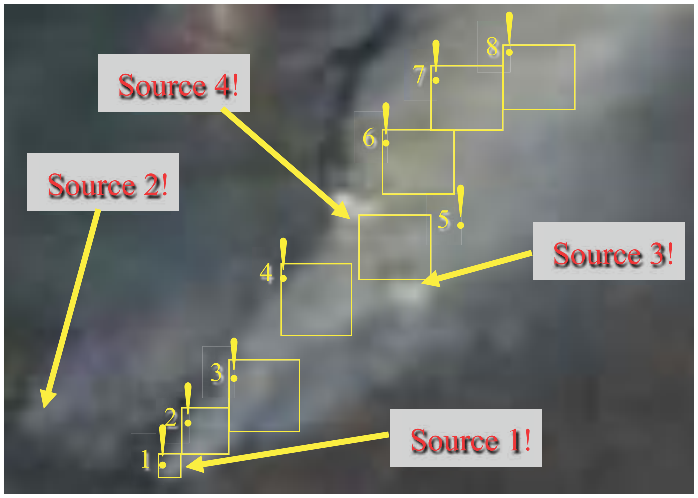
Oregon Fire Sept 04 2003
Orbit 19753 Blks 53-55 MISR Aerosols V17, Heights V13 (no winds)



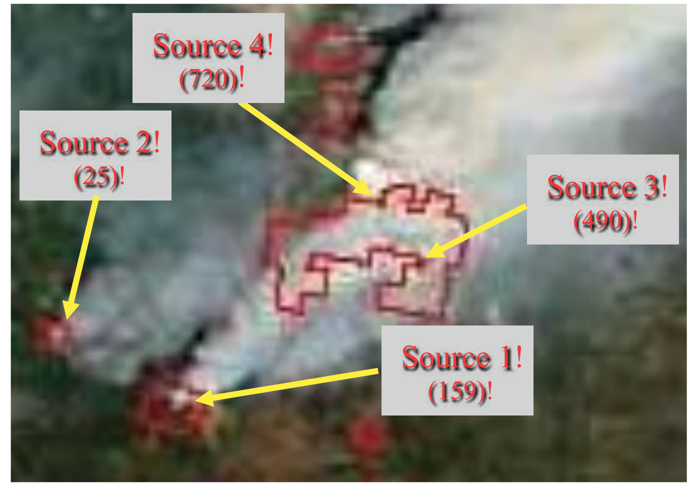
Kahn, et al., JGR 2007!

Detail of Wildfire Source Region

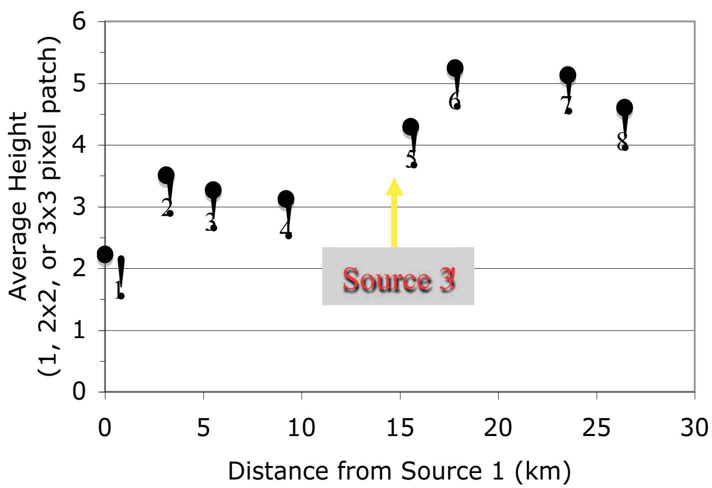
Oregon Fire Sept 04 2003



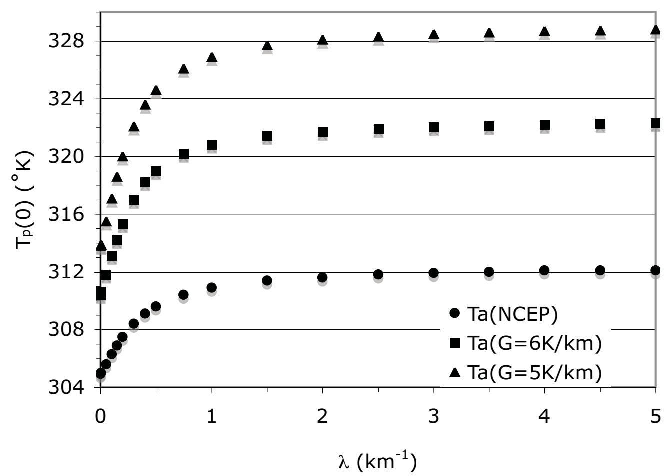
MISR Nadir 275 m Image



MODIS Image + Fire Power



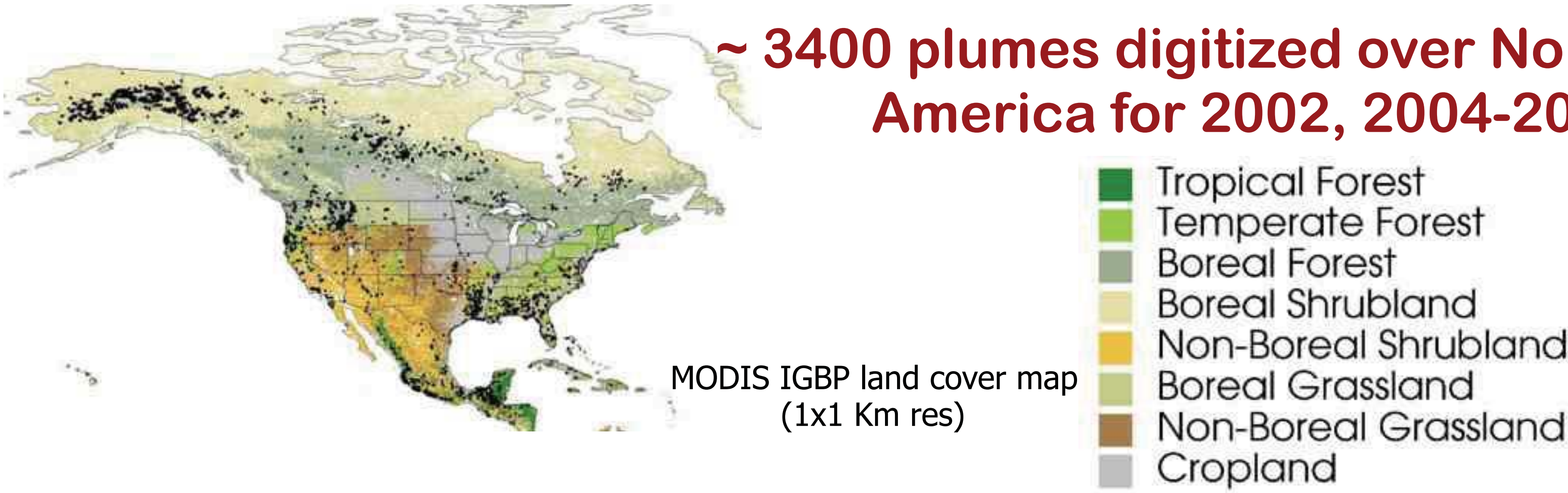
MISR Plume Heights for Sub-patches



Very Simple Plume Parcel Model

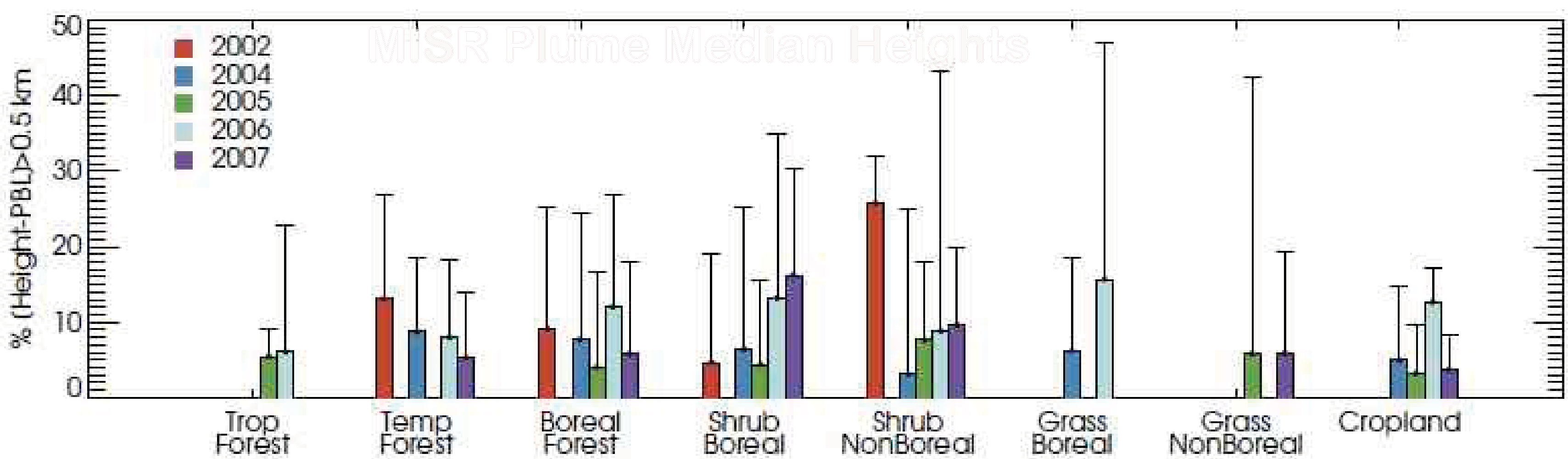
→ ***Broad swath + high spatial resolution*** needed to characterize sources!

N. America Plume *Injection Height* Climatology



~ 3400 plumes digitized over North America for 2002, 2004-2007

MODIS IGBP land cover map
(1x1 Km res)



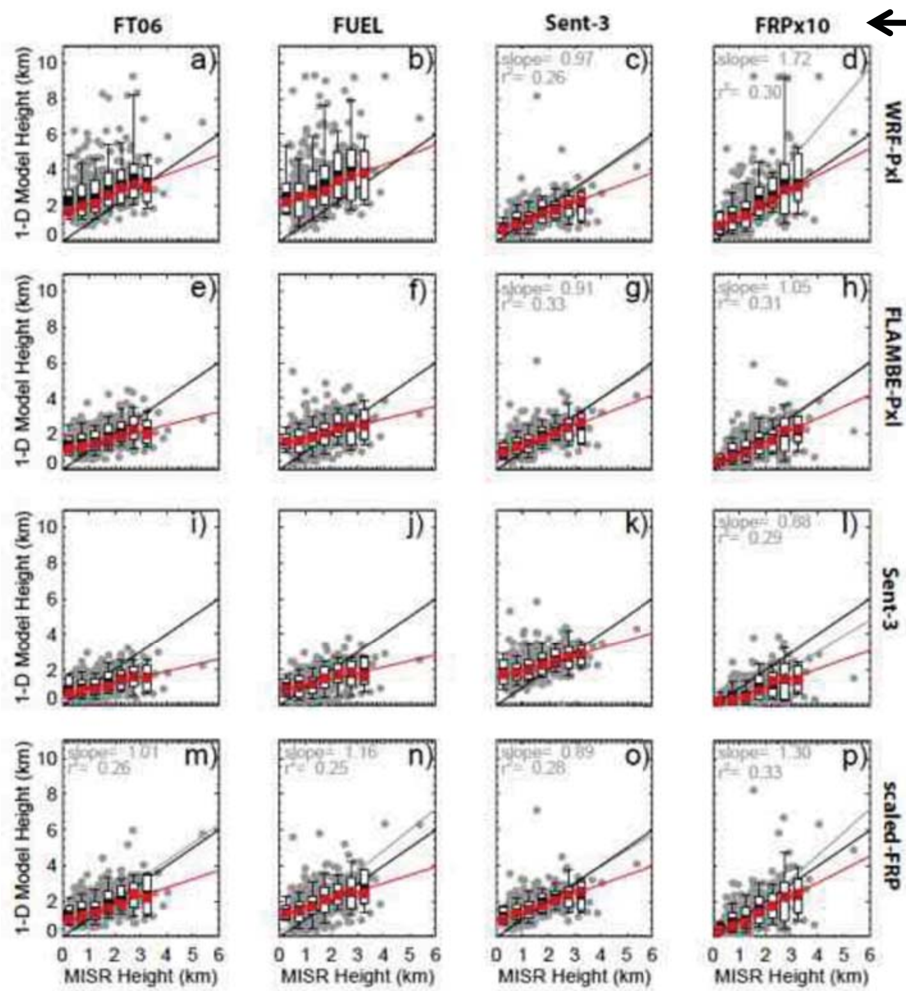
Percent of plumes >0.5 km ***above BL***, stratified by year and vegetation type!

Val Martin et al. ACP 2010

Evaluation of a 1D plume-rise model: Towards a parameterization of smoke *injection heights*

Heat Flux Options

Active Fire Area Options



To Constrain models:

Need to assess the

Parameterizations

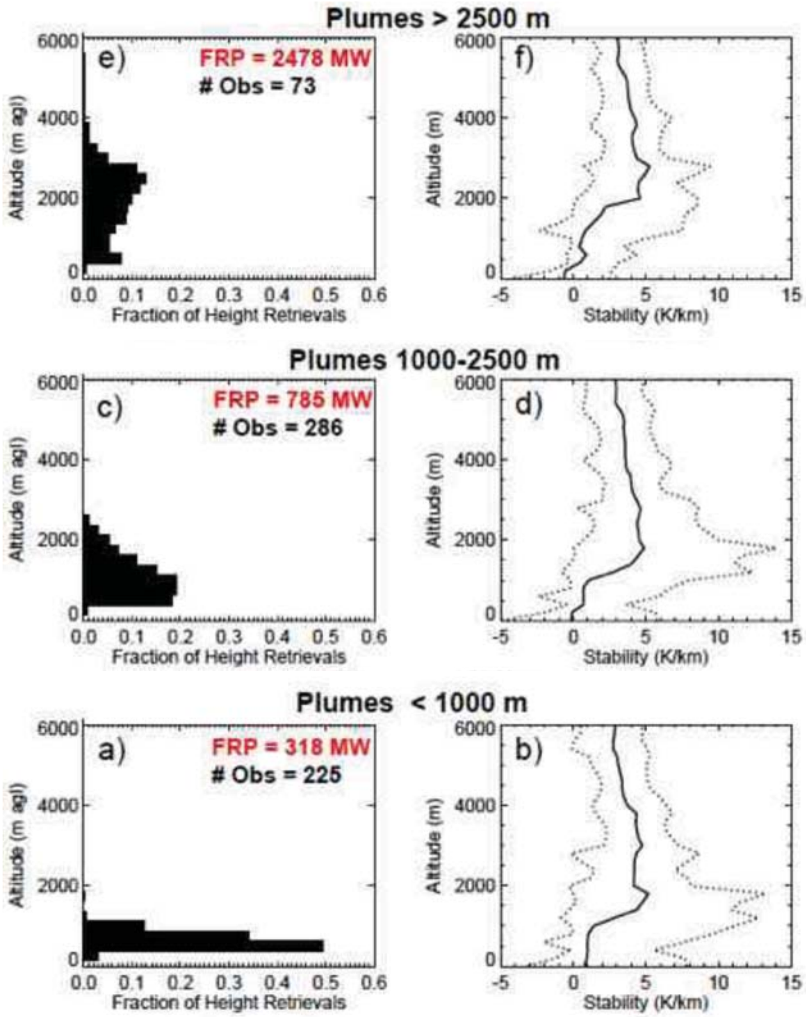
actually used!

1-D Plume-rise model heights vs. MISR-observed max. plume heights !

-- Models have ***lower dynamic range than observed***, but very variable

Val Martin et al., JGR 2012

Evaluation of a 1D plume-rise model: Towards a parameterization of smoke *injection heights*



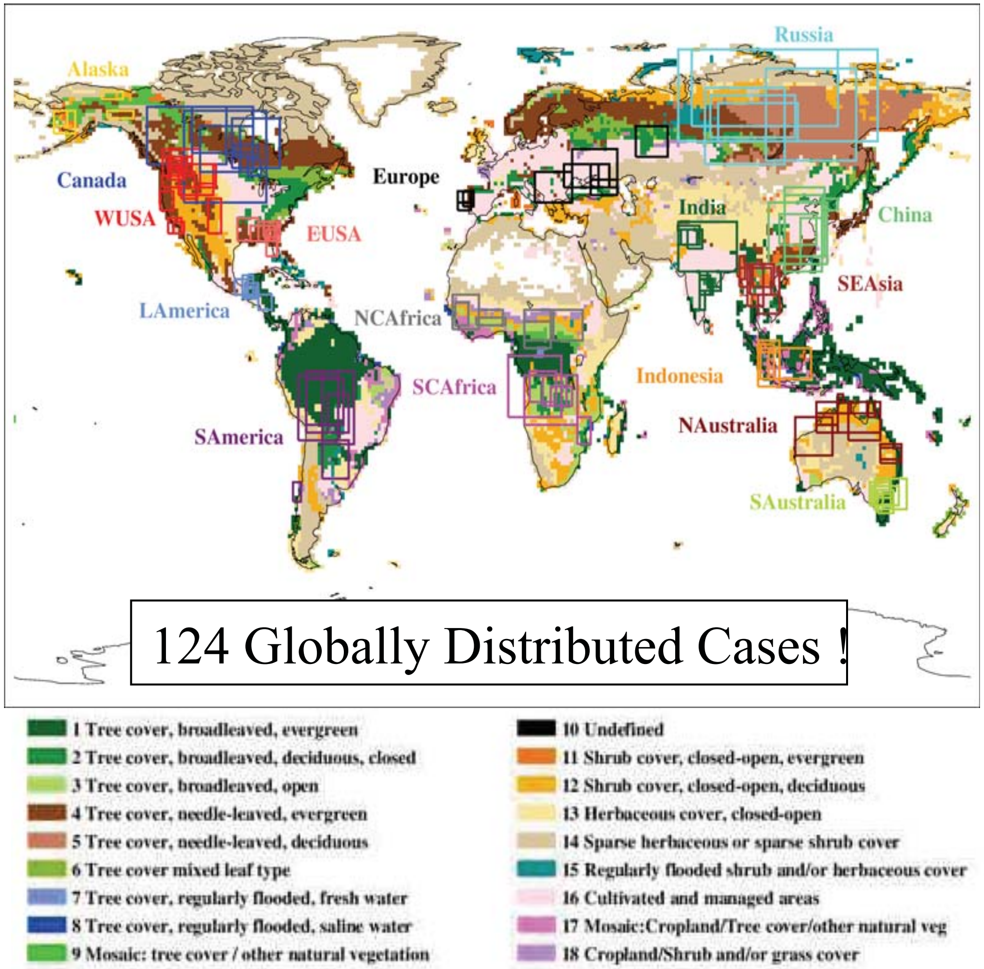
<u>The key factors</u>:!

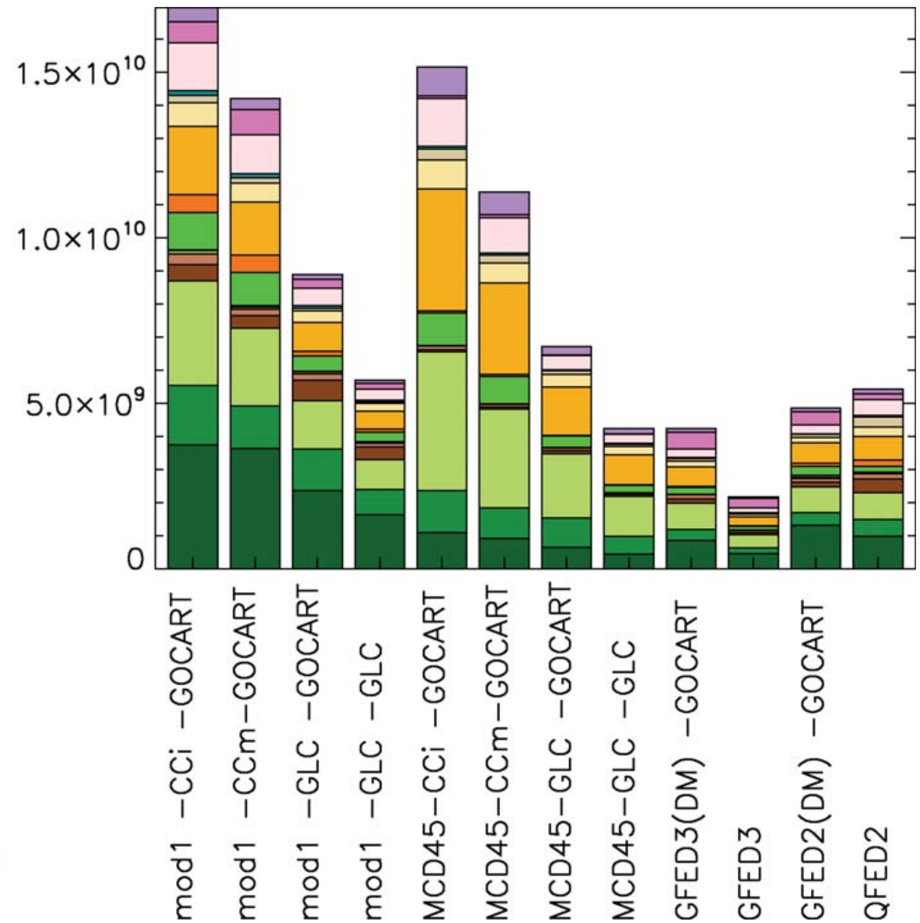
- ***Fire Energy***
  (fire area; heat flux, FRP)!
- ***Atmospheric Stability***
- ***Entrainment***

Plume height increases systematically as !
FRP increases and ***Atmospheric Stability*** decreases!

Val Martin et al., JGR 2012

)"1: 66/1: %,- . %0#"F0*5 10%15 %05#01+"/#%6 V/5B "00%/3+#/#A%6B /00/5#0%5"#$%&'!($&)*(+'



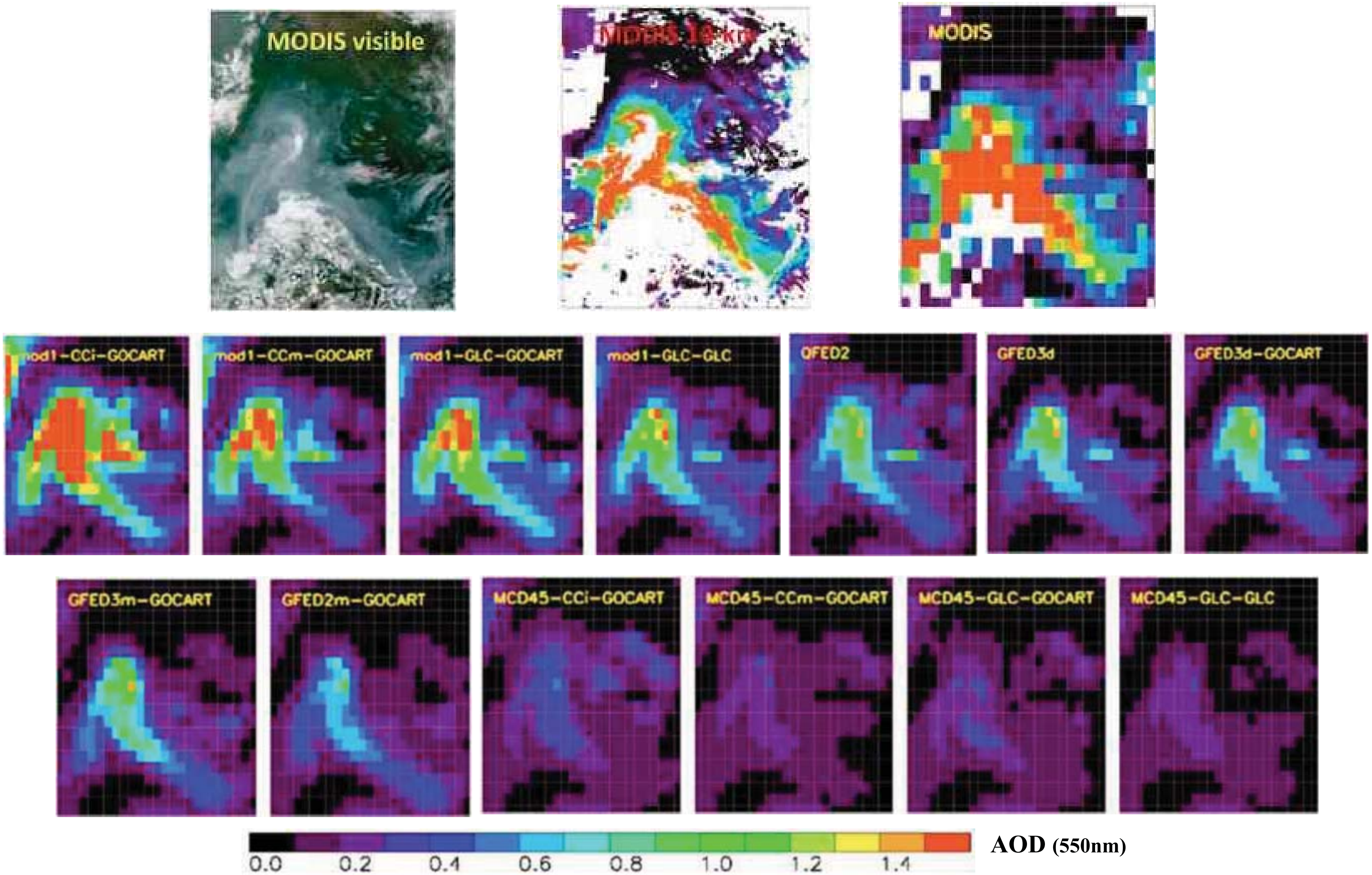


13 Smoke Emission Estimates!

Petrenko, Kahn, Chin, et al., JGR 2012

< - . T)X 5L, GE%51"6%56B #%- . %5B F"+/05#0%

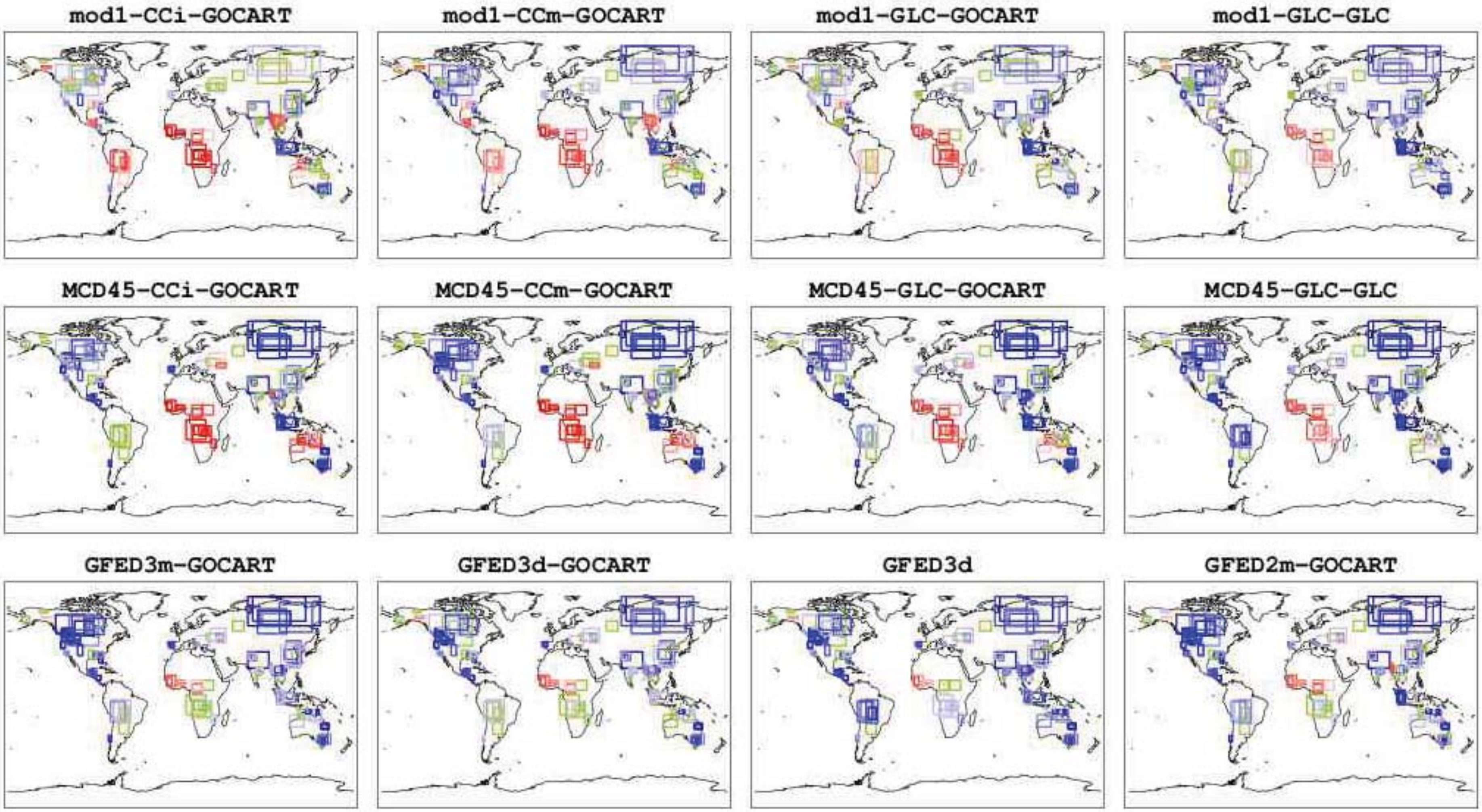
)"B F6 %"0: Y%/2: +/"%36 7%& %& ' W%



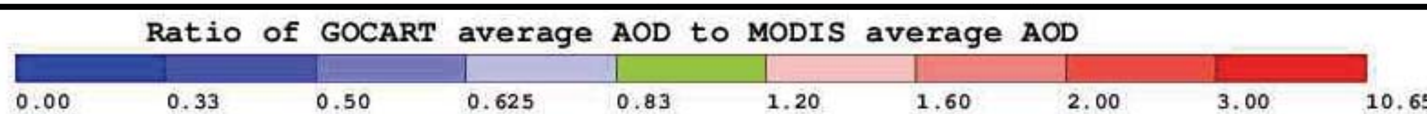
Petrenko et al., JGR, 2012

Ratio of GOCART to MODIS average AOD "

For each case, for 12 emission estimates

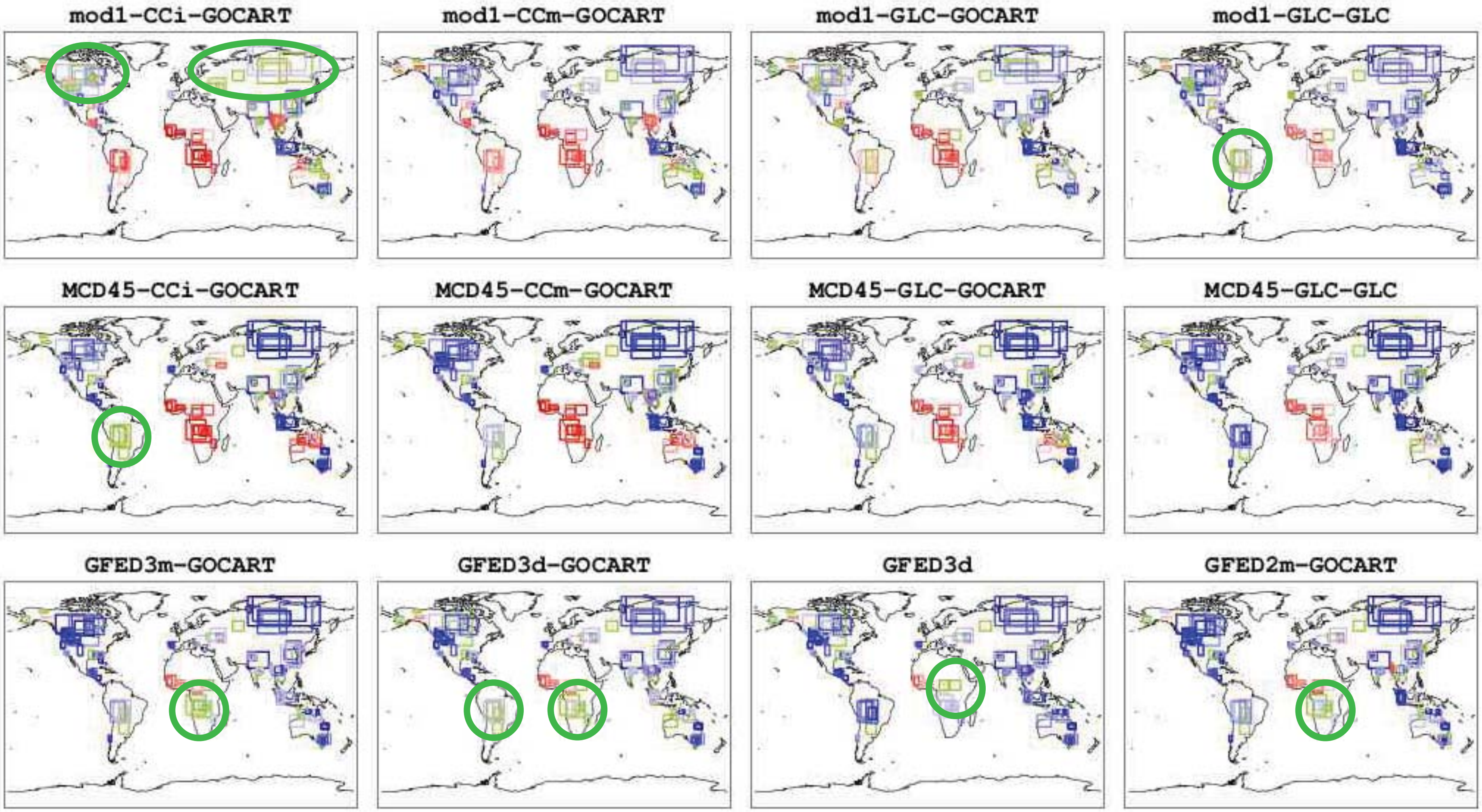


) 701: B "49%: A/5#"6%"Z : +#0[%5B : %"+"B : 1: +/R'45#0% 5+>%: Z : +/#%: +1"/#%: A/5#0%

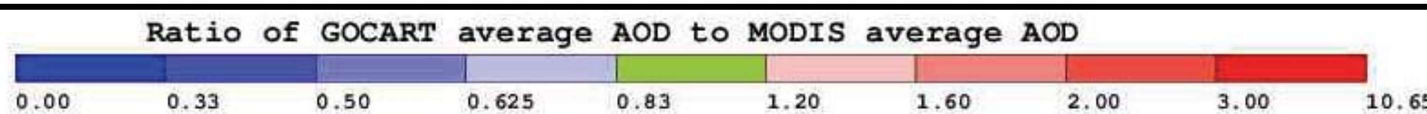


Ratio of GOCART to MODIS average AOD "

For each case, for 12 emission estimates



) 701: B "49%: A/5#"6%"Z : +#0[%5B : %"+"B : 1: +/R'45#0% 5+>%: Z : +%#%: +1"/#%: A/5#0%

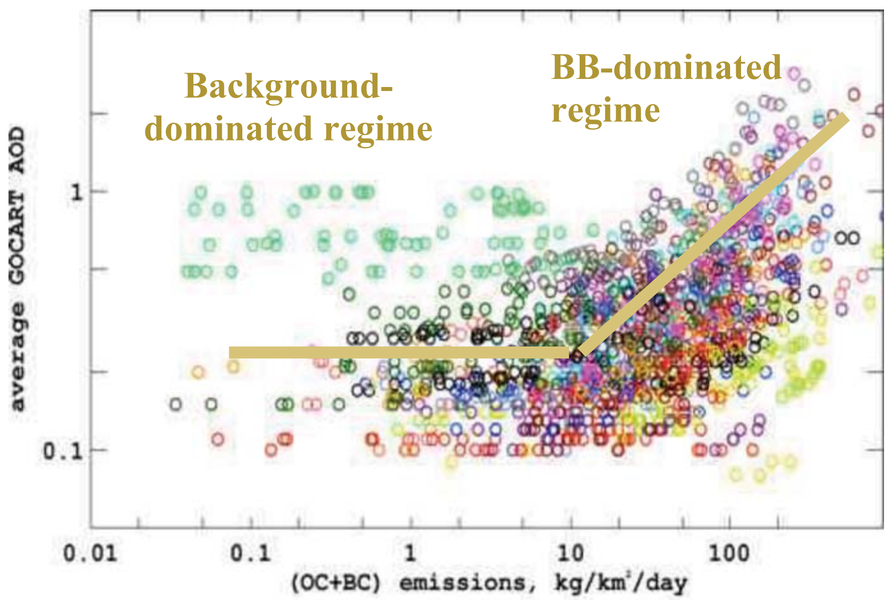


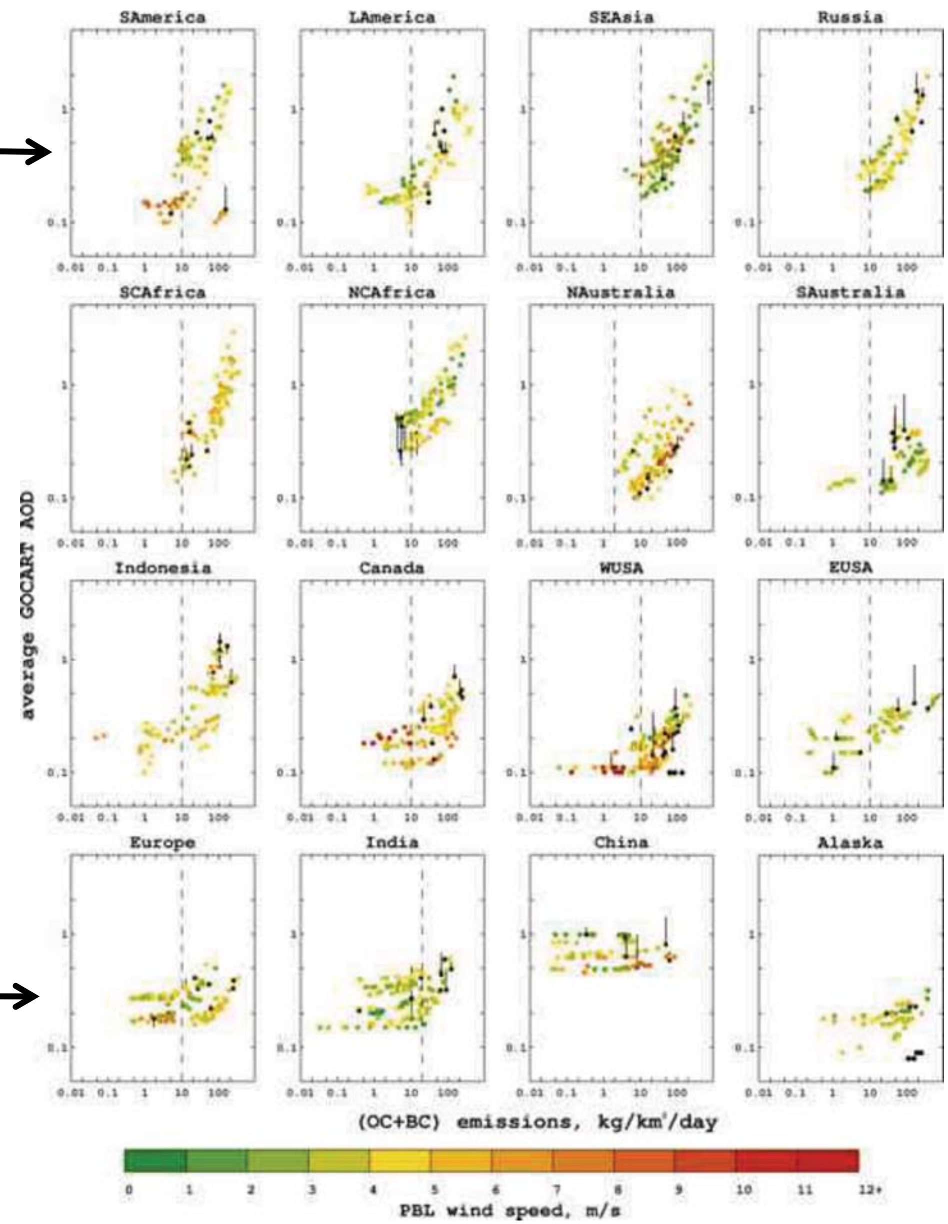
Quantitative Relationship Between Smoke Emission and AOD

Depends On

- ***Wind Speed at source***
- ***Background AOD***!

Steeper slope ~!
Lower wind speed!

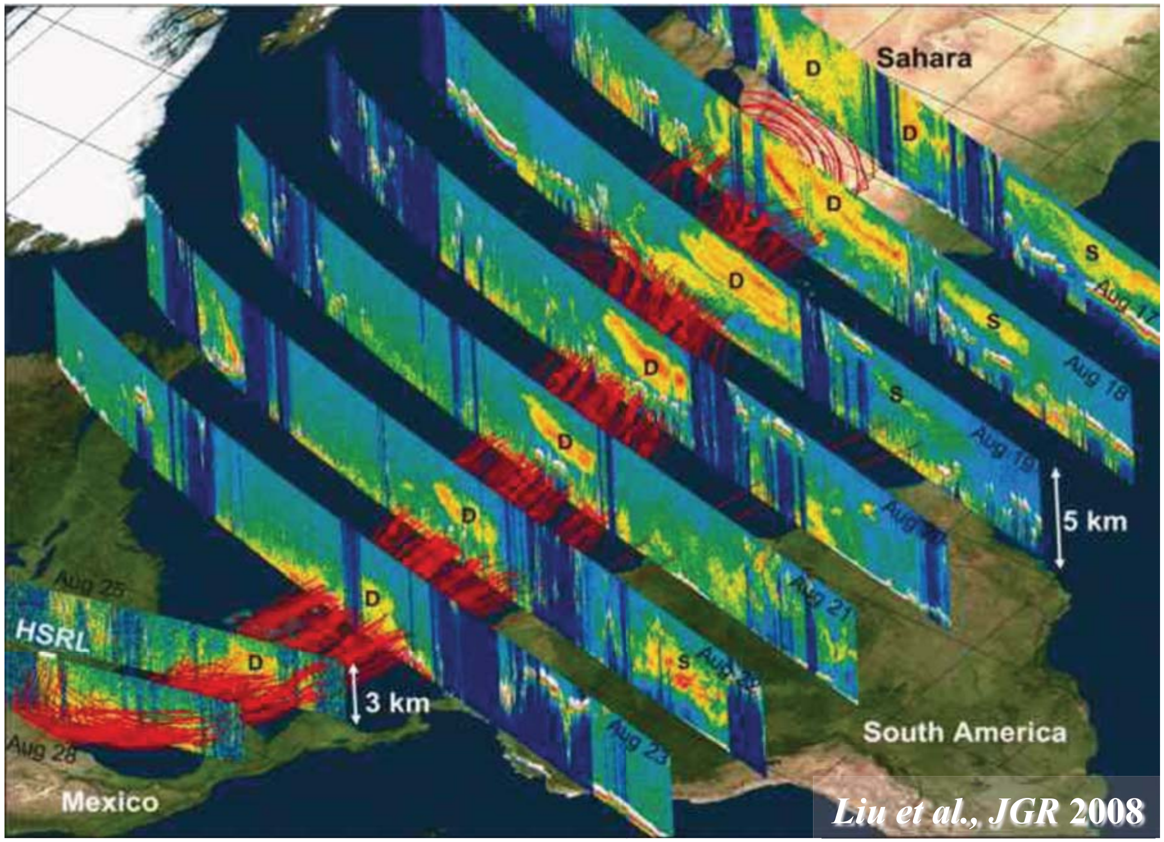




High background AOD ~!
Smoke plume insignificant!

Petrenko et al., JGR 2012

Aerosol Sources, Processing, Transports, Sinks: Lidar + Model



August 2007 Saharan dust "D" and smoke "S" event
mapped by CALIPSO 532 nm backscatter, with superposed!
model back trajectories and airborne HSRL observations!

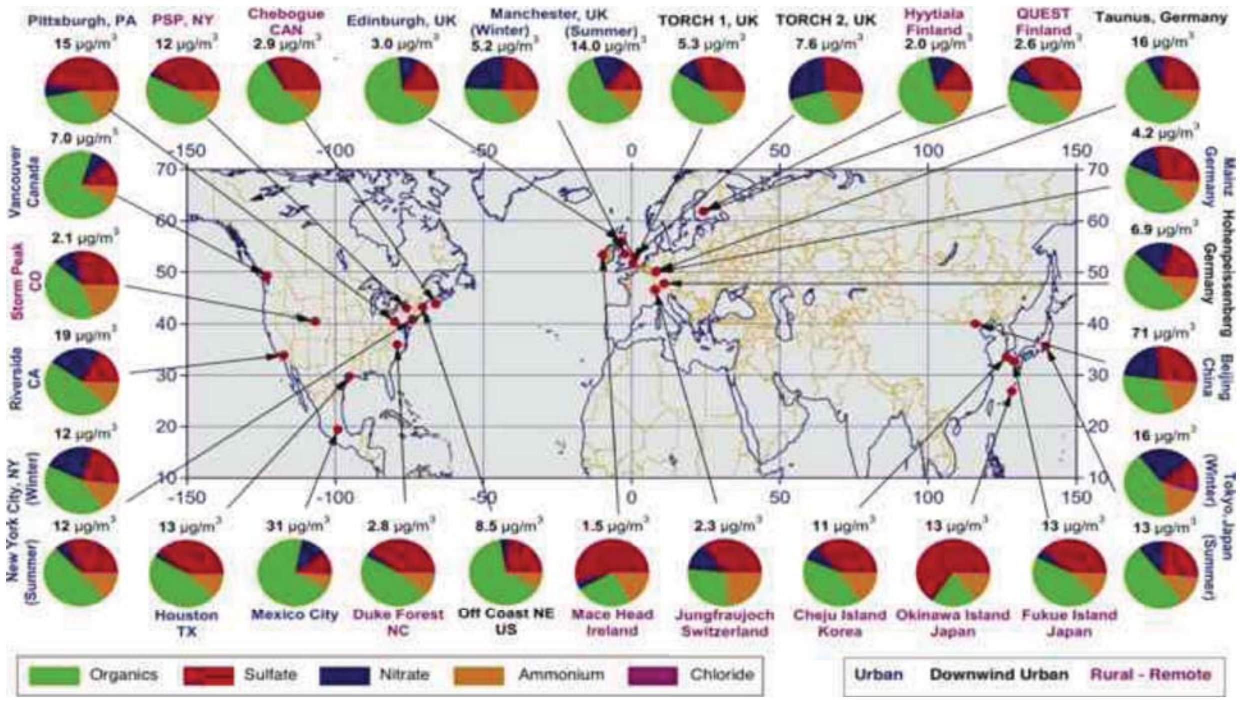
Piecing together the bigger picture. Consistency requires – !

- An understanding of the ***mechanisms*** governing aerosol evolution!
- Adequately constrained ***initial & boundary*** conditions!

Applications –

Air Quality!

Improving Air Quality Models



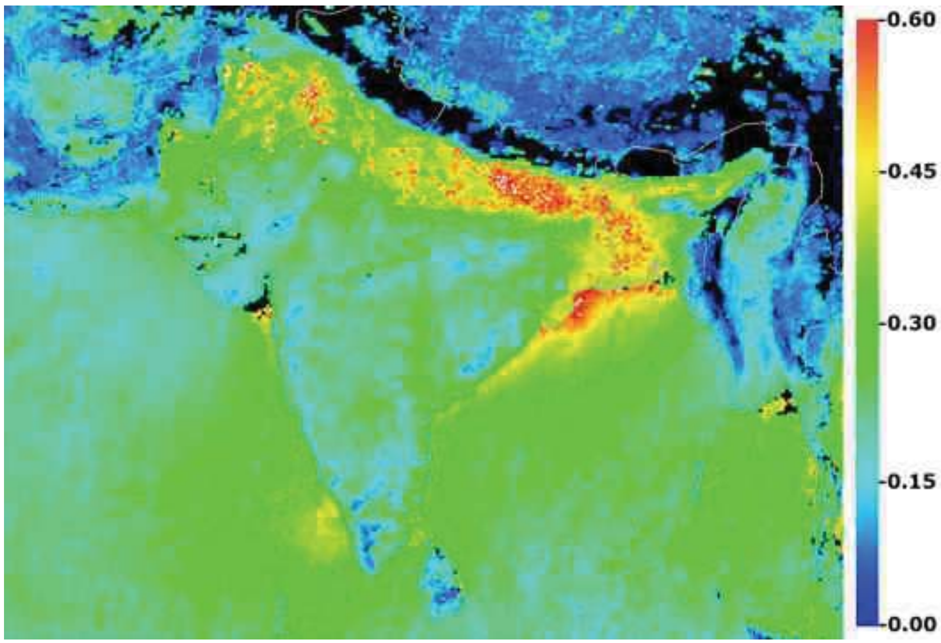
Zhang et al., GRL. 2007

Surface-based mass-spec aerosol composition measurements!

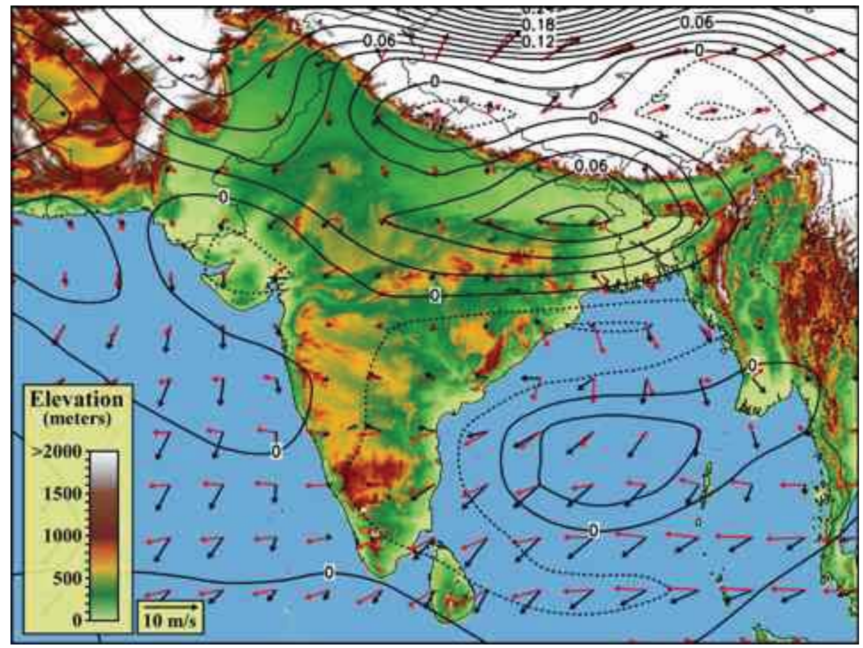
- **Need to isolate** ***Near-surface Aerosol Component***
- **Need sufficient** ***Spatial-Temporal Coverage*** **to capture** ***Severe Events***
- **Detailed** ***Chemical Speciation*** **often required**
- ***High Spatial Resolution*** **often required** (e.g., in Urban areas)

→ Recent efforts use models to parse satellite column AOD; speciate spherical particle fraction!
[*Y. Liu et al. JAWMA* 2007; *Martin and von Donkellar*, 2008]!

Pollution Aerosol Concentrated!
in Ganges Valley near Kanpur, India (MISR)!



MISR mid-visible AOD!
[**Winter**, 2001-2004; white --> AOD >0.6]!

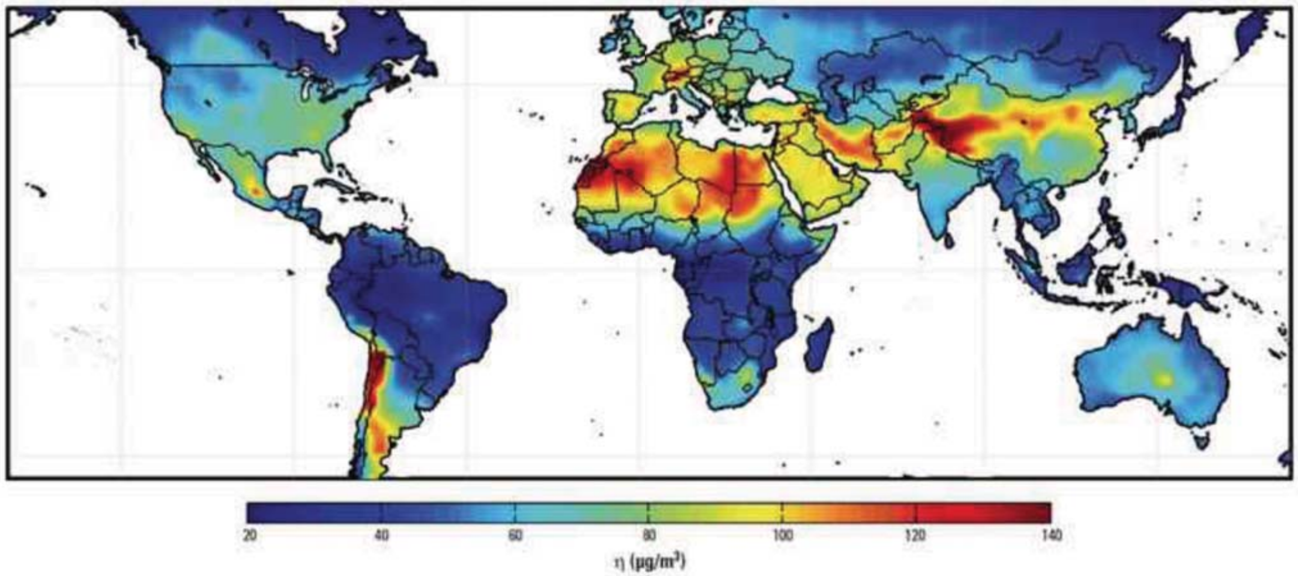


NCEP Winds + Topography!
[Black=surface; Red=850 mb; !
contours=vertical, solid=subsidence]!

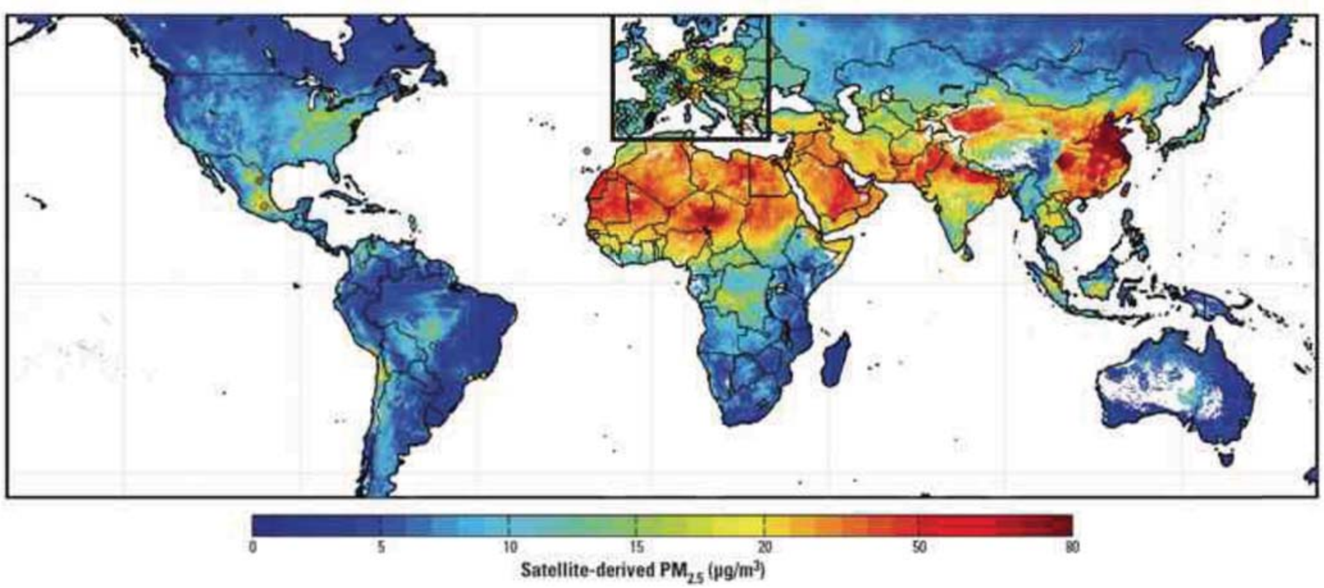
DiGirolamo et al., GRL, 2004!

Air Quality: BL Aerosol Concentration!

[MISR + MODIS] AOD & GEOS-Chem Vertical Distribution



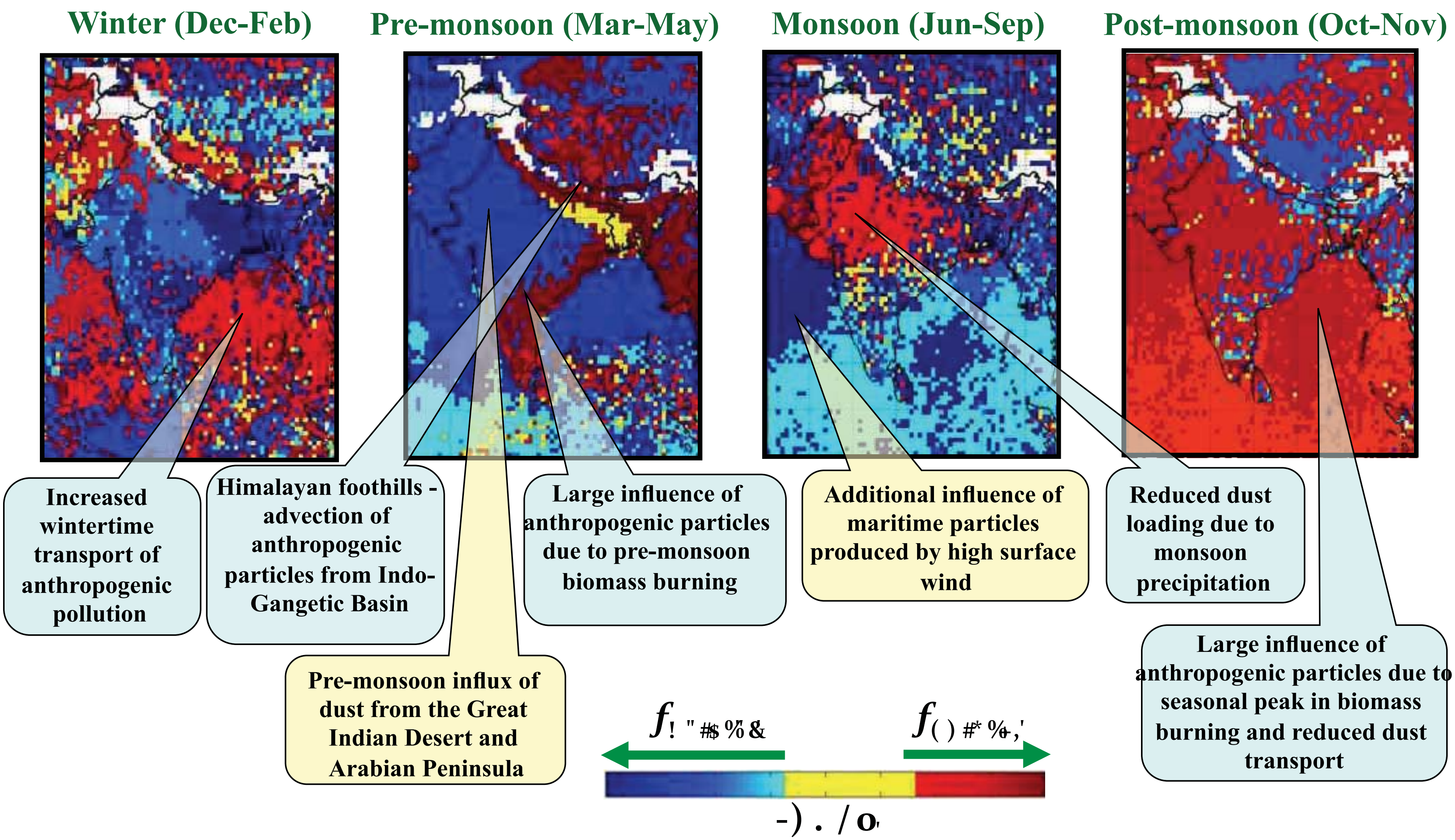
[BL $PM_{2.5}$] /
[Total-col. AOD]
2001- 2006



Derived
$PM_{2.5}$

Van Donkelaar et al., Environ. Health Prespect. 2010

Characterizing seasonal changes in anthropogenic and natural aerosols w.r.t. preceding season over the Indian Subcontinent!



Index uses MISR-retrieved particle shape and size constraints !
to separate natural from anthorpogenic aerosol!

Dey & Di Girolamo **JGR 2010**

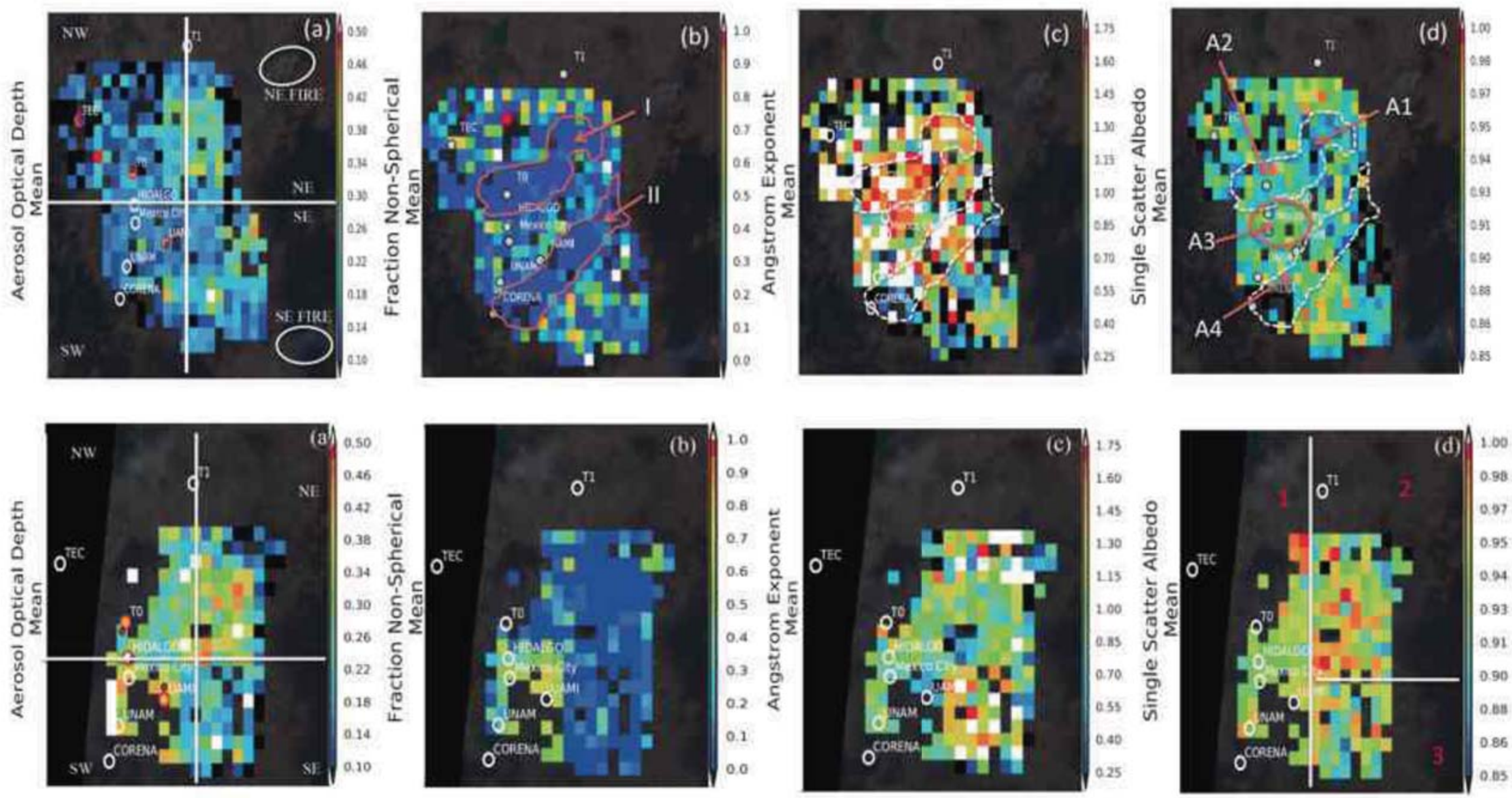
Mapping AOD & Aerosol Air-Mass-Type in Urban Regions!

INTEX-B/MILAGRO
MISR March 06, 2006
Orb 33062 Path 26 Block 75

Patadia et al.

Urban Pollution AOD & Aerosol Air Mass Type Mapping
INTEX-B, 06 & 15 March 2006

AOD! Fr. Non-Sph.! ANG! SSA!



March! 06 !

March! 15!

Aerosol Air Masses: ***Dust*** (non-spherical), ***Smoke*** (spherical, spectrally steep absorbing),! and ***Pollution*** particles (spherical, spectrally flat absorbing) dominate specific regions!

Patadia et al., JGR submitted

Over-Land Aerosol Short-wave Radiative Forcing w/Consistent Data

The slope of: !

!

TOA albedo vs. AOD

!

For data stratified by:!

!

Surface BHR

!

!

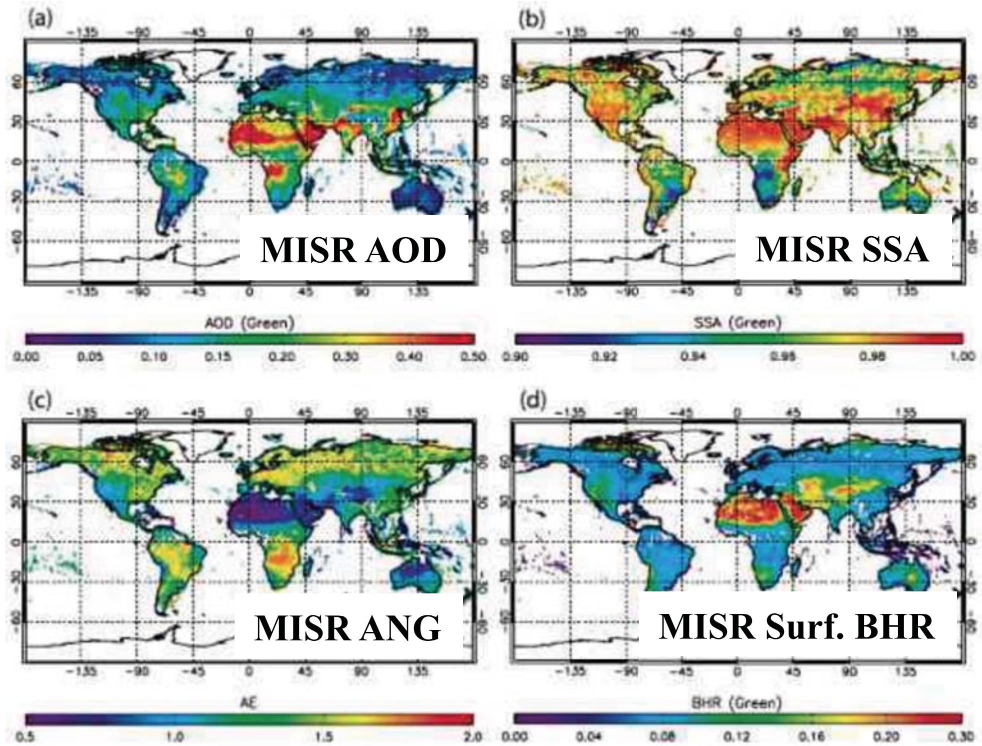
!

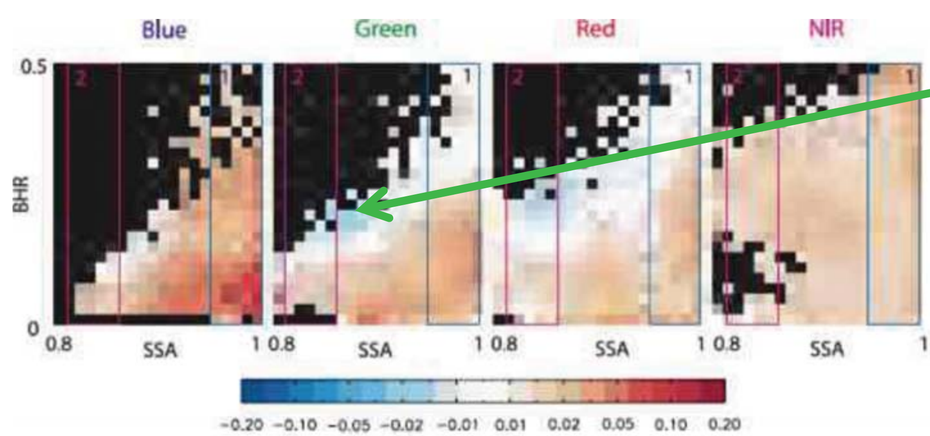
Produces: !

!

Spectral aerosol radiative efficiency

$(d!_{TOA}/d\forall_{mid\text{-}vis})$!



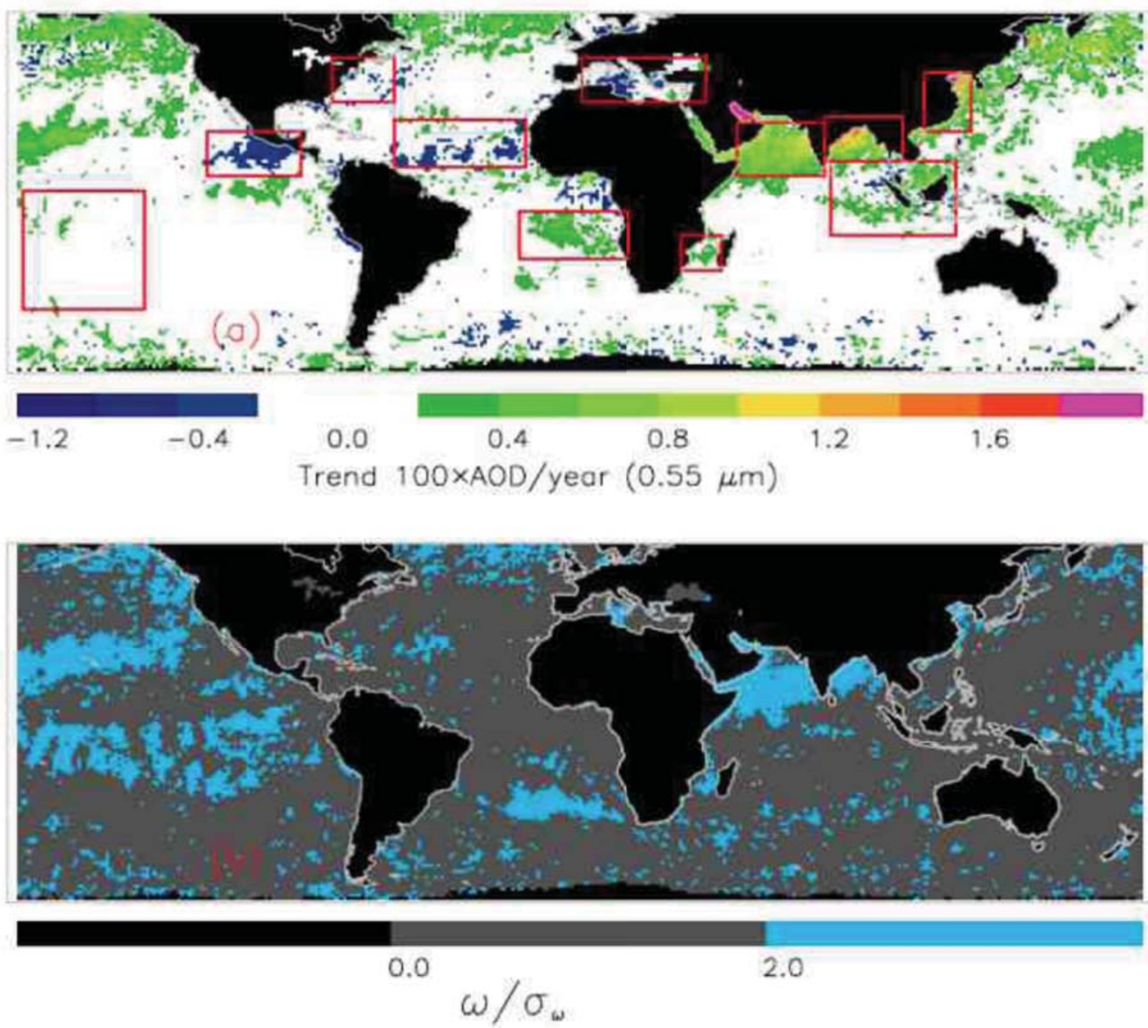


Bright surface!
+ dark aerosol!
= decreasing!
albedo w/AOD!

Depends on aerosol *microphysical* properties relative to surface albedo!

Y. Chen et al. JGR 2009

MODIS10-Year Global/Regional!
Over-Water AOD Trends !



Trend!

Statistical! Significance!

- Statistically ***negligible*** ***(±0.003/decade)*** ***global-average*** over-water AOD trend !
- $Statistically ***significant*** ***increases*** over the Bay of Bengal, E. Asia coast, Arabian Sea!

Zhang & Reid, ACP 2010!

Key Attributes of the MISR **Version 22** Aerosol Product!

- **AOT Coverage** – ***Global but limited sampling*** on a monthly basis!

!

- **AOT Accuracy** – Maintained even when particle property information is poor!

!

- **Particle Size** – ***2-3 groupings reliably***; quantitative results vary w/conditions!

!

- **Particle Shape** – ***spherical vs. non-spherical robust***, except for coarse dust!

!

- **Particle SSA** – useful for ***qualitative*** distinctions!

!

- **Aerosol Type Information** – diminished when ***AOT < 0.15*** or 0.2!

!

- **Particle Property Retrievals** – ***improvement expected*** w/algorithm upgrades!

!

- **Aerosol Air-mass Types** – ***more robust*** than individual properties!

PLEASE READ THE QUALITY STATEMENT!!!

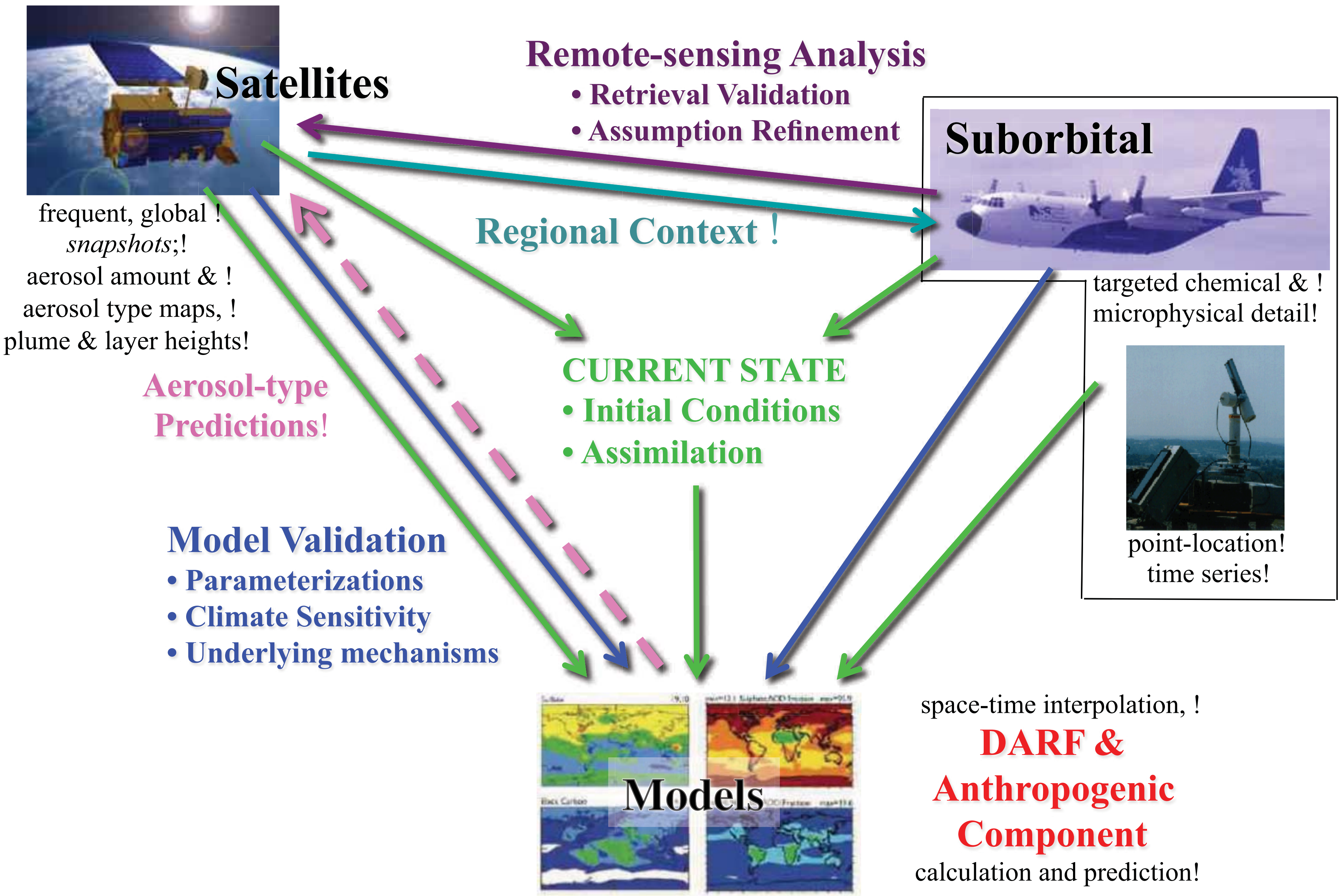
… and more details are in publications referenced therein

Current MISR & MODIS Mid-Visible AOD Sensitivities!

- MISR: **0.05 or 20% * AOD** overall; ***better over dark water*** [*Kahn et al*., 2010]!
!
- MODIS: **0.05 ± 20% * AOD** over dark target land!
  ! **0.03 ± 5% * AOD** over dark water [*Remer et al*. 2008; *Levy et al*. 2010]!
!
Based on AERONET coincidences (cloud screened by ***both*** sensors)!
!
- Global, monthly MODIS & MISR AOD ***is used to constrain IPCC models***

→***For global, Direct Aerosol Radiative Forcing (DARF), instantaneous measurement accuracy needed*** ***(e.g., McComiskey et al., 2008)*****:**

- ***AOD to ~ 0.02 uncertainty***
- ***SSA to ~ 0.02 uncertainty***



Kahn, Survy. Geophys. 2012